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A Feasibility Study on Utility-Scale Solar Integration in the Kingdom of Saudi Arabia

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A Feasibility Study on Utility-Scale Solar Integration in the Kingdom of Saudi Arabia

by

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Thesis

Presented to the Faculty of the Graduate School

of the University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Arts

The University of Texas at Austin

May 2010

Dedication

For mom and dad.

Acknowledgements

I would like to acknowledge my family for supporting my academic interest in renewable energy and making all of this possible. I would like to acknowledge all the UT professors for facilitating and instilling the necessary insight I have gained. I would like to acknowledge and thank Meridian Solar, especially Ryan Hunter, Andrew McCalla, and Linda Haas, for giving me the experience I needed to succeed in my thesis and career as well as getting me excited about solar.

Abstract

A Feasibility Study on Utility-Scale Solar Integration in the Kingdom of Saudi Arabia

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The University of Texas at Austin, 2010

SUPERVISOR: David Spence

Due to the vast fossil fuel wealth, the country of Saudi Arabia is experiencing a dramatic growth in both population and GDP. Therefore there is a growing demand for water and energy to meet these needs. All of the electricity that is generated is sourced from crude oil and natural gas. All natural gas production is used domestically and there are no net imports or exports. Due to many constrains on the natural gas supply, there is a slow shift in the generation mix going towards crude oil based power generation. This study assessed the viability of utility scale solar integration into the Saudi Arabian electric mix to potentially relieve some demand pressure for natural gas consumption as well as reduce green house gas emissions. Parabolic trough concentrated solar power technology was chosen as the primary technology for utility scale integration. A total of five scenarios were calculated. The scenarios include the following, base case, 5%, 10%, 15%, 20% solar integration in terms of installed capacity. Two sets of net present values were calculated. The net present values of each scenario were calculated. A second set of net present values was calculated with a projected increase in electricity prices. The natural gas and crude oil offset from the four solar integration scenarios were calculated using the base case forecasted natural gas and crude oil consumption from power generation. As expected, natural gas and crude oil consumption decreased when there was an increase in solar integration. The expected carbon dioxide offsets were calculated for each scenario. There was a decrease in carbon dioxide emission as solar integration was increased. Finally, all of these analyses were used as criteria for a decision analysis using the analytical hierarchy process. Depending on the decision maker's importance on the determined criteria, solar integration in the Kingdom of Saudi Arabia is achievable.

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Chapter I: Introduction

Saudi Arabia is considered one of the leaders in fossil fuels production. With a vast resource of natural gas and crude oil, Saudi is experiencing continual growth in GDP. Even in 2009 during a global recession, the Kingdom experienced a positive growth in GDP of 0.2% (Central Intelligence Agency, 2009). With a growing country in both wealth and population, the infrastructure will need to facilitate and support the growth. Currently, Saudi Arabia is experiencing some growing pressure, especially with regards to energy.

Even though the Kingdom has a vast resource of fossil fuel, the country is experiencing shortages in natural gas production. All natural gas produced is for domestic consumption only (Energy Information Administration, 2008). The country does not export or import natural gas. The current production and transport infrastructure cannot handle the increase in demand for natural gas. There are many reasons why there is a massive growing demand for natural gas. In order to facilitate a diversification of the Saudi economy, the price of natural gas is highly subsidized. The petrochemical and industrial sectors are experiencing a boom due to the cheap natural gas feedstock. There is also a growing demand for electricity. Approximately half of the electricity generated is sourced from natural gas. Along with the subsidized natural gas, the price of electricity is also subsidized. The rationale behind this the government wants to support its citizens and share the oil wealth. With cheap electricity and natural gas, there is no incentive to conserve energy.

The installed capacity of Saudi Arabia is expected to more than double by 2030 (Saudi Electricity Company, 2008). The country is currently looking into building more power plants that run on crude oil in the future due to the production issues of natural gas. These issues will be discussed later on in this report. There is also a campaign for increased natural gas exploration.

Saudi Arabia not only has a vast resource of fossil fuel, the country has a vast solar resource. The country also has a lot of undeveloped desert land. On the surface, there is a potential for solar power integration. In the current economic environment, solar integration could be a viable option to help address the country's growing demand for electricity.

This report is designed to shed some light on the viability of solar integration in Saudi Arabia. In order to properly evaluate this, an assessment of several topics revolving around solar integration is vital. The current electric utility environment will need to be evaluated and proposals for improvements will be needed. A solar technology assessment should be performed. There are many variations of solar electric technology and this report will weigh in the pros and cons of each type of technology. An assessment of financial viability will need to be performed. Not only does the cost of solar require to be figured in, but there are other associated costs that need to be addressed, such as operation and maintenance costs. Electricity generated from solar power will need to be modeled and integrated into a forecasted electricity demand. Since it is expected that solar power will offset natural gas and crude oil consumption, there will need to be an assessment on how much fossil fuel will be offset. Since global climate change and the issue with green house gas emissions is a concern, there will be an interest in how much carbon dioxide will be offset with the integration of solar power. With all of these factors, this report will attempt to address this issue in depth. To summarize, this report will address the following:

- Solar technology assessment and selection
- Current utility landscape in Saudi Arabia
- Financial assessment of solar integration
- Natural gas and crude oil avoidance
- Carbon dioxide offset

In terms of the degree of solar penetration, this report will assess five scenarios with varying degrees of solar integration with a set deadline of 2030. In this case the five scenarios are the following:

- Base case (business as usual)
- 5% solar integration
- 10% solar integration
- 15% solar integration
- 20% solar integration

Once all of these scenarios and different topics have been assessed, a decision analysis will be performed using the analytic hierarchy process. The decision analysis will go over several options with varying degrees of importance of the predetermined criteria. The goal of this section is not to recommend a scenario but to highlight how a recommendation can be reached depending on the importance of certain criteria.

This report not designed to be used as a detailed roadmap for the integration of solar power in Saudi Arabia. The primary objective of this report is to simply assess the viability of solar integration and address the pros and cons of solar integration with regards to the topics that have been mentioned.

Chapter II: Solar Technology

This section will go over several solar electric technologies that are currently being utilized as well as go over technologies still being researched upon. There are two popular methods of generating electricity from solar energy. These are solar thermal and photovoltaic. Each of these technology types has their pros and cons. Photovoltaic solar technology can be broken down into three sub categories that produce electricity in a similar manner, i.e. photovoltaic effect. These include photovoltaic, thin film and concentrated photovoltaic (CPV). Concentrated solar power uses heat generated from the sun to generate heat, which is then used to spin a turbine. There are varying technologies that use this basic form of power generation, including parabolic trough, power tower, and a dish system.

The primary objective of this chapter is to assess the pros and cons of commercially viable solar technologies and select an appropriate technology to use for solar integration in Saudi Arabia.

Photovoltaic

Photovoltaic solar technology uses the photovoltaic effect to generate direct current (DC) electricity. As mentioned before, there are varying types of photovoltaic technologies that are in the current market. With regards to concentrated photovoltaics, it is debatable that CPV is a viable utility scale option. The market for this type of solar technology is small since the primary driver for CPV is the reduction in silicon usage in the product and with the recent decline in silicon costs has lessened the competiveness and advantage of CPV over other photovoltaic products that have high silicon content (Mehos, 2004).

There many key advantages photovoltiacs. This type of technology has the advantage of being a modular product. Photovoltaic products are manufactured and sold as modules. Therefore shipping, transportation and installation issues are most likely reduced due to the increased ease in handling solar modules over projects that call for on sight heavy construction and the installation of larger size sections that would call for heavy-duty construction machines.

Solar modules make up a large portion of total installed cost but over the years, the cost of modules has seen a steady decline, mainly due to cheaper manufacturing costs and economies of scale. The figure below contains a graph of module retail prices over a span of 10 years in both the United States and European market (Solarbuzz, 2010). These prices reflect the cost of solar modules with a minimum module capacity size of 125 watts and are measured in price per watt.

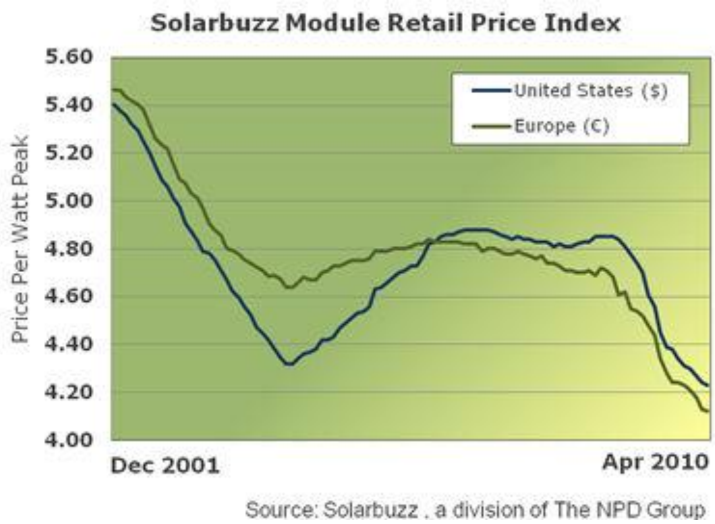


Figure 1: Module Retail Price Index

According to a study conducted for the California Energy Commission, the primary cost drivers of a photovoltaic system include the following (Charles O'Donnell, 2009):

- Solar modules: Cost of silicon, wafers, and solar cells
- Inverters
- Installation: High efficiency modules mean fewer modules to install.
- Steel price
- Balance of system

It is expected that with economics of scale, increased efficiency and lower manufacturing costs, the overall installed cost of PV projects will eventually become competitive against conventional sources of electricity generation. It is just a matter of time. A study conducted by the European Photovoltaic Technology Platform has forecasted that photovoltaics will be able to compete with consumer and peak prices by 2010 to 2020 and beyond that, it is expected that PV technology will be able to compete at a wholesale level (European Photovoltaic Technology Platform, 2007).

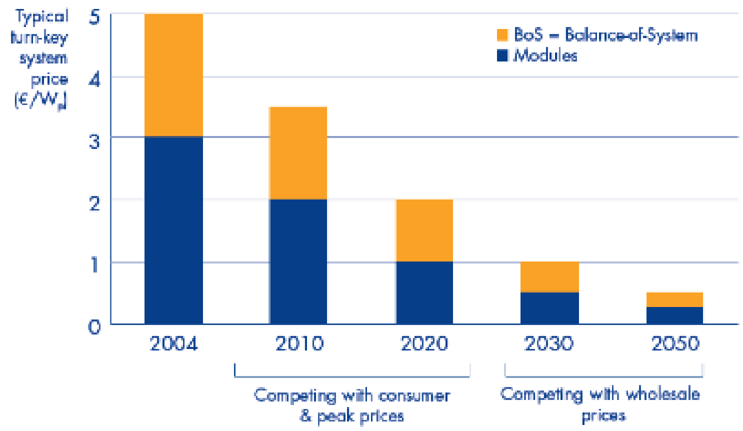


Figure 2: Typical turnkey system price (European Photovoltaic Technology Platform, 2007)

There are several drawbacks to utility scale photovoltaic projects. The primary drawback with this technology is that there is no economically available energy storage option. Therefore, electricity is only produced when the solar resource is available. Therefore the overall capacity factor of PV systems, depending on the region, is relatively small. Photovoltaic systems in Arizona have a typical capacity factor of 19%, which has a similar solar resource as Saudi Arabia (Curtright, 2004). In other words, throughout the year at all times, the solar array is only producing at 20% of the total potential the system could generate. This is specifically due to the intermittency of the solar resource.

Concentrated Thermal Power

Concentrated thermal power (CSP) produces electricity by using a series of mirrors and lenses that concentrate and focus sunlight onto a thermal receiver. Within this receiver the heat derived from the sunlight is then transported to a steam generator or engine, in which the electricity is produced. There are three basic types of CSP technology, parabolic systems, dish/engine systems and central receiver towers.

Within the thermal realm of electricity generation, there are three major subcategories. These are the typical generalized descriptions of CSP technology. There are aspects within this that delve into increasing energy efficiency and capacity.

Concentrated thermal power has seen a renewed growth and interest especially in Spain and the United States. As of April of 2009, 1.2 gigawatts of CSP plants are under construction globally. And by 2014, it is expected that an additional 13.9 gigawatts are to be constructed. Most of this new construction is due to the new legislation in Spain. This is mainly through Spain's new feed-in tariffs (European Photovoltaic Technology Platform, 2007).

The study also reports that there is a different bias in CSP technology selection between the U.S and Spain. EER has estimated that 96% of the planned CSP construction in Spain will be parabolic trough technology, while in the U.S., only 40% is expected to be of that type. This is mostly due to the Spain's risk aversion to developing technology. Parabolic trough technology is the most established CSP technology to date with readily available historic and current cost and performance data.

A major advantage CSP has over PV technology is the ability to pair the system with a backup generator or thermal storage. Since CSP technology is very similar to conventional power plants, a natural gas backup system can be integrated into the system. Therefore, during time when the there is shade or when the sun is not up, a backup natural gas generator can be used to generate electricity using the power plant's turbine. Thermal storage is also another back up option. Thermal storage essentially stores heat generated from the CSP system and stores it using a specialized heat transfer fluid in a storage tank. When there is a reduction or elimination of the solar resource, the heat stored can be dispatched to generated electricity. Typical thermal storage can extend the power generation of a CSP plant by an extra four hours. (Owens, 2003).

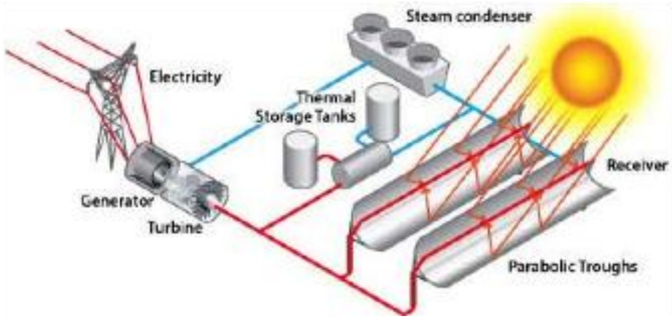


Figure 3: Overview of a CSP System (Owens, 2003)

Trough

Parabolic trough technology is laid out in a linear fashion with curved mirrors; troughs are typically laid out in parallel rows, known as a collector field. The troughs are laid out along the north south axis so that the collector field can track the sun from the east to the west. The curved mirrors are designed to focus the solar radiation on to receivers, tubes that run along the length of the mirrors, strategically placed at the focal line of the parabolic mirror.

Many of these trough systems use a hybrid design. When the CSP no longer generate electricity from the sun, a fossil fuel back up will supplement the solar output. Natural gas-fired or a gas steam boiler will be used. This system allows for an uninterrupted electricity generation.

Some trough designs can incorporate thermal storage, in which heat generated from the sun during the day can be stored so that the electricity can be generated from the stored heat. This in turn can generate heat for a couple hours after the sun has set.

There is also a different design, known as the linear Fresnel reflector system. This system similarly, has a series of mirrors that are placed linearly. The mirrors themselves are not curved, but the azimuths are position so that the solar radiation from multiple rows of mirrors is reflected to a receiver (tube) position above the mirrors (NREL). Nevada Solar One is the second largest concentrated solar power plant in the world with a capacity of 64 MW and was completed in 2006 and went online in June 2007.

The Andasol solar power station is the first commercial parabolic trough solar thermal power system in Europe. Located in the province of Granada in Spain, the CSP has a capacity of 50 MW. This is a series of three sections, Andasol One, Andasol Two and Andasol Three. Andasol One came online in November 2008. Andasol Two and Three are currently being developed and constructed and are planned to be completed in the spring of 2009 and fall of 2011 respectively. Andasol One cost around $380 million.

In the U.S., Florida Power and Light is planned to construct the second largest solar-thermal power plant with a capacity of 75 MW by mid-2010. The name of the project is the Martin Next Generation Solar Energy Center and will be located near Indianatown, Florida. The power plant will not have thermal storage and it is expected to cost in the vicinity of $500-600 million. The government of Florida has recently passed several bills that have loosened state-controlled lands to develop renewable energy projects as well as creating tax credits for renewable energy development.

Dish System

Another type of solar concentrating power plant is the dish/engine system. As the name implies, the CSP is built like a satellite dish, focusing all of the solar radiation at a centralized focal point connected to the dish. The dish system uses a dual-axis system to accurately track the sun for maximum heat collection.

The engine of the system is a Stirling system, which utilizes the fluid heat to move pistons, providing mechanical energy, which is then used to run a generator or an alternator. Other options for electricity generation using a dish/engine system are microturbine and concentrating photovoltaic modules. These systems can also be combined with natural gas to produce continuous electricity production.

Each dish can produce 5-50 kW of electricity and can interconnect to each other to increase generating capacity. According to the Energy Efficiency and Renewable Energy, a branch of the Department of Energy, dish/engine technology is not commercially viable yet.

Power Tower

The power tower system is similar to the dish system but instead utilize individual ground mounted mirrors, also known as heliostats, each positioned to reflect solar radiation to a focal point on a centralized tower containing a receiver. The heat transfer fluid in the receiver is then converted to steam, which is then used to generate a steam turbine located at the foot of the tower.

There have been several power towers that have been constructed and studies. The Solar One was the first large-scale power tower built. Located in the Mojave Desert, east of Barstow, California, the Solar One had a 10 MW capacity. It was completed in 1981. The power tower was eventually redesigned and named Solar Two in 1995. The main difference is heat-transfer fluid. Solar One used oil and water. Solar Two used a molten salt, a mixture of sodium nitrate and potassium nitrate. This provided limited heat storage and a buffer when during intermittent solar radiation during the day, such as cloud cover. The plant was decommissioned in 1999.

Technology Choice

Due to the available information, as well as being the most popular choice for Spain in which 96% of new CSP project development, parabolic trough CSP will be the primary focus on. There is a lot more information available in regards to cost as well as performance. The other CSP technology is either still in the development stage or is not ready to be scaled up. The parabolic trough technology is not necessarily the preferred choice should a utility or development company decide to build utility scale projects but due to the available cost and technical information available, parabolic trough CSP would be better suited in this report to properly assess solar integration.

With regards to photovoltaics, this technology was not chosen for on primary reason. The primary reason PV was not chosen was due to the very low capacity factor and the lack of energy storage

Chapter III: Saudi Electric Utility

Saudi Arabian Electrical Grid and Transmission

According to the Energy Information Administration, Saudi Arabia's electrical demand is growing at annual rate of 5-7%. According to Saudi Arabia's Water and Electric Ministry, the demand will double by 2025 from the 2007 installed capacity of 35.9 gigawatts to an estimated increase of 35 gigawatts by 2025 (Ministry of Water and Electricity, 2010).

There are several issues that need to be addressed in order for Saudi Arabia to meet this increasing demand growth. The three important issues are the following: increasing capacity, feedstock acquisition and transportation and transmission and grid issues.

Saudi Arabia houses the largest oil reserves in the world and the fourth largest natural gas reserve; it is no surprise that the electrical generation feedstock is fossil fuel based. The majority of the electrical feedstock is natural gas. It is no surprise that the natural gas demand is growing in conjunction with the electric demand.

Saudi Government and Electric Utility Structure

There are several branches that regulate the energy market. Overall, the Ministry of Water and Electricity (MWE) oversees and supervises all electricity activities in the Kingdom. The key responsibilities of the MWE are to recommend policy legislation and long-term electricity planning (Dincer, Hussain, & Al-Zaharnah, 2004).

Within this ministry, the actual generation, transmission and distribution of electricity falls upon the responsibility of the Saudi Electric Company (SEC). The SEC is a stock company with the majority shareholder being the Saudi government owning 81% of the SEC shares (Al-Swaha, 2007). The company was formed in 2000 by merging the 10 regional power companies into one, through the supervision of the MWE (Al-Ajlan, Al-Ibrahim, Abdulkhaleq, & Alghamdi, 2006).

In order to regulate electricity prices and ensure quality and reliable electricity, the Electricity Services Regulatory Authority was formed in 2001 (Al-Ajlan, Al-Ibrahim, Abdulkhaleq, & Alghamdi, 2006). As seen in Figure 4, the three main government controlled areas of the electricity sector is the MWE, the SEC and ERA, with the MWE overlooking the other two departments.

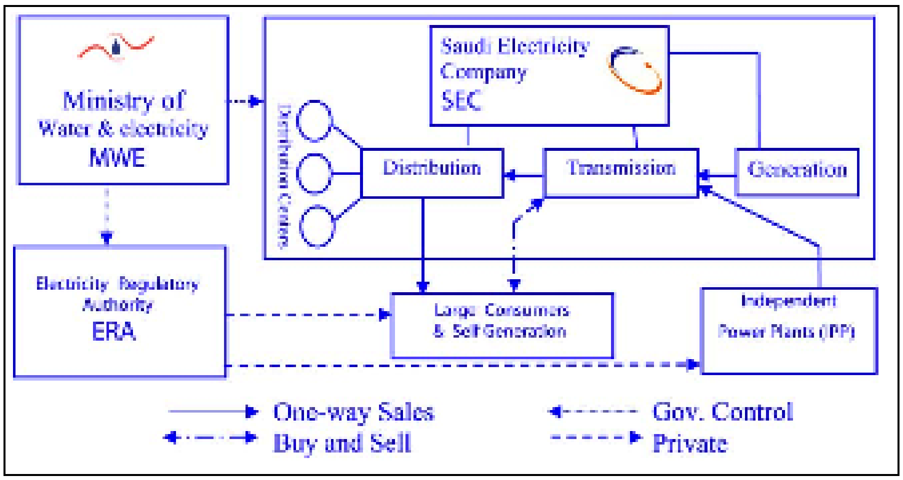


Figure 4: Institutional framework of the electrical power sector (Al-Ajlan et. al, 2006)

Generation

Saudi Arabia is expected to expand their electricity capacity to 75 gigawatts by 2020 according to an extensive study conducted by the Ministry of Water and Electricity (MWE) and the Electricity and Cogeneration Regulatory Authority (CRAEC)(Saudi Electric Company, 2008). The capacity of the Kingdom is estimated to be around 41 gigawatts as of 2009 (Saudi Electricity Company, 2008). Therefore there is an expected doubling of capacity demand in about 10 years, an estimated 34 gigawatts in additional capacity. As reported by the EIA, Saudi Arabia will be spending an upwards of $120 billion to meet these demands.

Figure 5, depicts the growing capacity and consumption since 1995. Every year, additional capacity is needed to meet the demand. On average, Saudi Arabia is experiencing approximately 6% annual growth in energy demand.

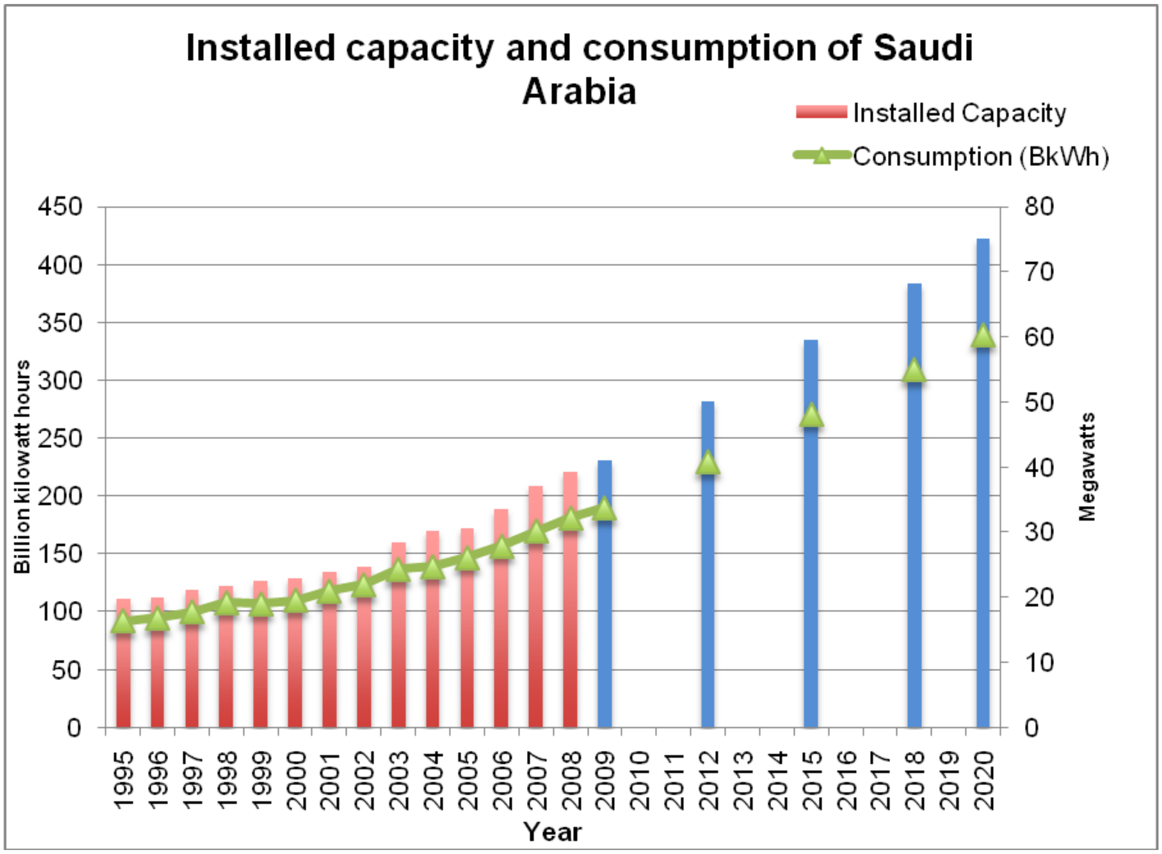


Figure 5: Installed Capacity, expected capacity and Consumption of Saudi Arabia (Saudi Electricity Company, 2009)

The electricity generation mix is all sourced from fossil fuels with a majority sourced from natural gas. As can be seen in figure 6, a majority of the generation is sourced from gas-fired power plants. The other sources of electricity are the steam power plants, combined cycle and diesel generators, respectively (Saudi Electric Company, 2008). There are currently two oil and gas cogeneration facilities, totaling 300 mW and a 350 mW cogeneration plant is currently being constructed (Energy Information Administration, 2008). Based on a study conducted by the MWE and CRAEC, additional generation will be produced using steam power plants located in the coastal areas and combined cycle or gas power plants in the interior regions (Saudi Electric Company, 2008).

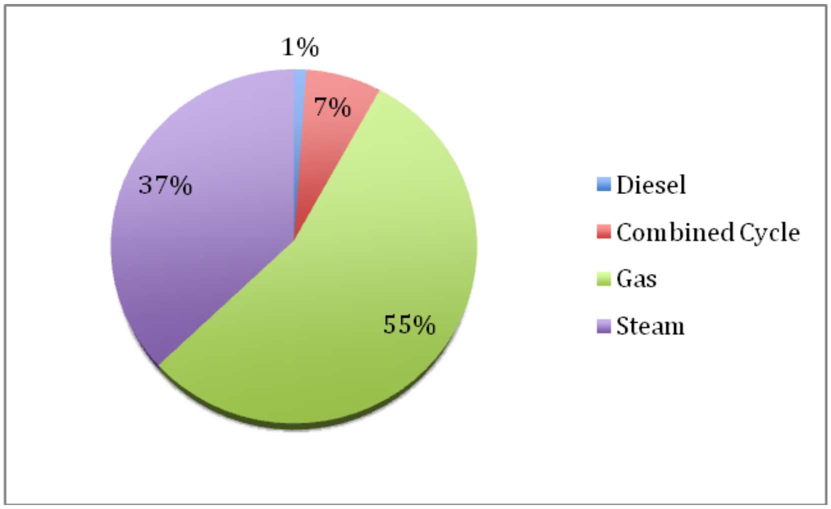


Figure 6: Generation Mix in 2009 in Saudi Arabia (Saudi Electricity Company, 2008)

Currently, it is difficult to access load profiles of the Saudi Arabia. Al-Ajlan et. al., in 2006, were able to source the load profiles of 2001 (Figures 7 and 8). Due to the hot climate of Gulf region, there is a high demand during the afternoons to cool down buildings, creating a peak demand in the afternoon to late afternoon, when the temperature rises. This is even greater during the summer than the winter. It should be noted that air conditioning is used throughout the year.

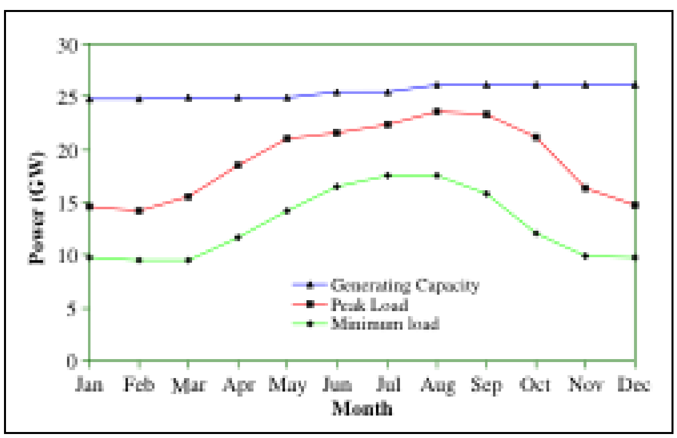


Figure 7: Electricity load profile by month (Alnatheer, 2005)

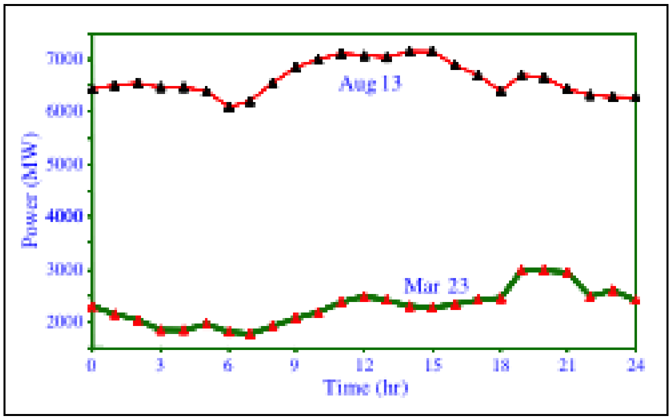


Figure 8: Daily load profile in the Riyadh region (Alnatheer, 2005)

Saudi Electric Company Independent Power Producer Program

The SEC has recently initiated an IPP program. This program facilitates private involvement in utility scale electric power development (Saudi Electric Company, 2008). The program is implemented as a build, own and operate (BOO) model (Al-Swaha, 2007). The primary reasons for the SEC to promote IPP development, is due to the increasing demand for energy, which in part creating a diversification of investment sources from private foreign and domestic sources. This will also allow the SEC to divert more funds to transmission and distribution upgrades (Al-Swaha, 2007).

The ownership of the project is a conglomeration of the SEC, 10% stake, the developers, 60% stake and a third party, if any or additional SEEC or developers stake (Al-Swaha, 2007). The company in charge with the development and financing of the power plant is then provided with a long-term power purchase agreement from the SEC. The SEC is also responsible for fuel requirements, land allocation, as well as any transmission upgrades

According to the SEC website, there are a total of 6 IPP projects in the pipeline, with the earliest coming online in 2012.

Transmission

Due to the rapid increase of energy demand and expansion, there is growing concern with the current transmission infrastructure of Saudi Arabia. At this moment there are five regional transmission networks; East, West, South, North, and Central (Alnatheer, 2005). The SEC is currently in the middle of interconnecting all the regional grids. Should Saudi Arabia decide to interconnect all of the regional grids, it is estimated that over 20,000 miles of additional power transmission and distribution lines will be needed beyond the current 150,000 miles of lines (Energy Information Administration, 2008). According to the SEC 2008 Annual Report, there are several projects planned to interconnect several of the regions, including interconnecting the Central and Western regions, interconnecting the Western Region with the Southern region and interconnecting the Central region with the Southern region.

Beyond the national interconnection, Saudi Arabia is participating in the interconnection of all of the countries in the Gulf Cooperation Council (GCC). Countries that will be interconnected with Saudi Arabia include Bahrain, Kuwait and Qatar, which can be seen in Figure 9. This makes up the North Grid. The South Grid consists of the United Arab Emirates and Oman (GCCIA, 2009). Currently the North Grid is complete and the South Grid and the interconnection of the North and South Grid are currently under construction (GCCIA, 2009).

Figure 9: GCC Interconnection Scheme (GCCIA, 2009)

There are several major motivating factors that lead to the agreement of interconnecting all of the GCC countries. Reducing the generating capacity in each system by sharing power reserves. Sharing spinning reserves to cover emergency conditions and provide emergency support during black outs. The interconnection will lower operating costs by using more economic generation units. Finally, the GCC interconnection could provide an opportunity to export energy to neighboring Middle Eastern countries beyond the GCC and potentially Europe (Al-Asaad & Ebrahim, 2008).

Overall, there is a need to improve the national and regional transmission through interconnection, which is all underway and should be completed within the next several years. The primary aim for the transmission upgrade is to meet the growing power demand and facilitate additional added capacity that will be needed in the near future. In the 2009 GCC Summit in Kuwait, the joint GCC electricity-linkage project was officially launched with a cost of $1.6 billion spread across the six countries (Zawya, 2009).

Natural Gas Production and Consumption

All of the feedstock that is used for electricity generation is fossil fuel based, which includes natural gas, crude oil and diesel. In the past, the primary feedstock was natural gas. Recently, crude oil has become a primary source due to natural gas supply constraints (Figure 10).

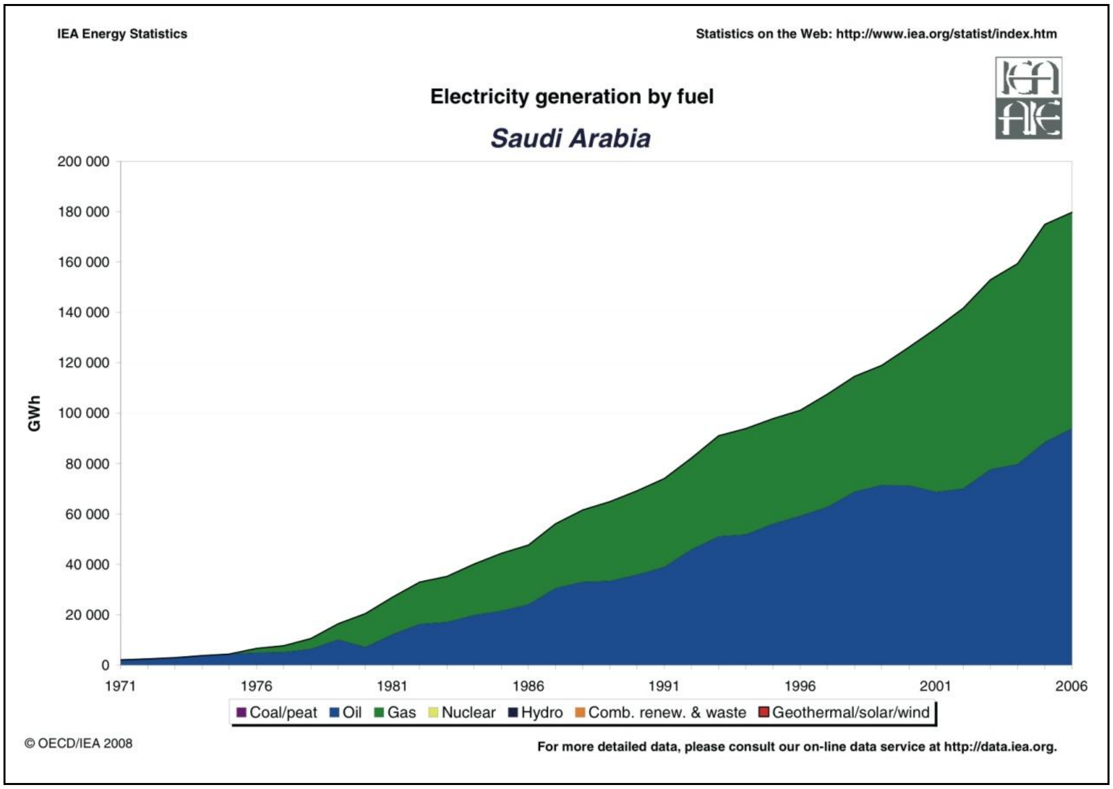


Figure 10: Electricity Generation by Fuel (International Energy Agency, 2008)

Currently, Saudi Arabia's natural gas market is strictly domestic. Therefore, there is absolutely no export of natural gas or plans to do so. As of the end of 2008, Saudi Arabia has the 5th largest proven natural gas reserves of 267 trillion cubic feet, behind Russia, Iran, Qatar, and Turkmenistan, respectively (Europe's Energy Portal, 2009).

Currently, the price of natural gas is at a highly subsidized cost of $0.75/mmBTU (Ministry of Foreign Affairs, 2008). This rate has been the same since the early 1990's when the rate was increased from $0.50/mmBTU (APS Review Downstream Trends, 2005). There have been suggestions to increase the price of natural gas to $1.50/mmBTU by 2011, but there has not been any indication of actually increasing the rates (APS Review Downstream Trends, 2005). To counteract this growing demand, Saudi Arabia has issued a royal decree on the drop in price of crude oil for electricity generation of $0.45/mmBTU (Energy Information Administration, 2008).

Saudi Arabia is currently encountering problems with meeting the growing demand for natural gas from both the industrial/petrochemical sector and the electricity sector. It is estimated that by 2030, consumption of natural gas will be at 14.5 billion cubic feet per day, double of 2007's consumption of 7.1 billion cubic feet per day (Energy Information Administration, 2008). According to the EIA (2008), about 57% of the natural gas reserves are associated. This has become the primary bottleneck in natural gas supply, since Saudi Arabia has crude oil production quotas. Therefore, a majority of the natural gas produced is dependent on crude oil production. Saudi Aramco is has outlined a plan to initiate efforts to explore for non-associated natural gas with a plan of discovering at least 50 trillion cubic feet by 2016 (Energy Information Administration, 2008).

Renewable Energy Development in Saudi Arabia

Even though there are no immediate plans for renewable energy development at a utility scale, Saudi Arabia has delved into research and some development in renewable energy applications, mostly in solar and wind energy. A royal decree issued by King Abdullah of Saudi Arabia called for the development of nuclear energy for power production and water desalinization purposes (Abdul Ghafour, 2010). This includes the establishment of the King Abdullah Nuclear and Renewable Energy City in Riyadh.

Small scale solar research commenced in 1969 and the King Abdulaziz City for Science and Technology (KACTS) began to develop solar energy technology at a larger scale in 1977 (Alawaji, 2001). The Energy Research Institute within KACTS headed many research and development projects in solar energy technologies, including several international joint projects (Alawaji, 2001). The primary project initiated in 1977 was the Saudi Solar Village Project. It was spearheaded by the Saudi Arabian National Center for Science and Technology and the United States Department of Energy (Miller, 1983). According to the agreement, each country would each provide $50 million for the technical solar projects.

The largest project was an off grid photovoltaic application for three villages using a 350 kilowatt concentrator photovoltaic system with a diesel-powered generator as well as a battery bank for backup (Miller, 1983). The primary objective for this solar village was to provide a village with off grid electricity, since many villages in the Kingdom do not have access to the electric grid.

In 1982, KACST and the Federal Ministry of Research and Technology at Germany commenced a joint solar thermal project using a solar electric Stirling engine concentrator. Two dishes with a capacity of 50 kilowatts were installed to test both off grid and interconnected applications.
The KACST and other research institutions had several other solar energy projects that delved into other areas such as hydrogen production, seawater desalinization, solar water pumps, solar dryers and refrigeration (Alawaji, 2001).

Recently, Saudi ARAMCO, the Kingdom's state oil company and Japanese oil refiner, Showa Shell Sekiyu have plans to start a solar power project. The key objective is similar to the Solar Village, to provide small-scale solar power plants to supply electricity to local communities. The system size is planned to be between on to two megawatts. Instead of using concentrated PV modules, they will use CIS (copper, iridium and selenium) thin-film. If the pilot project proves successful, the two companies plan on creating a joint venture and build other small-scale plants in other parts of the Middle East, South Asia, Africa and Latin America (Backwell, 2009).

Another notable project is the joint research between the Energy Research Institute at KACST and the National Renewable Energy Resources (NREL) based in Golden, Colorado. The objective of the project was to create a solar resource for possible siting (KACST and NREL, 1998). Over the last 40 years, there has been some interest in solar energy within the Saudi Arabia. But there has not been an aggressive interest in solar energy, which may be a different story in the future. Saudi ARAMCO has shown some interest in solar technology and in fact are interested in pursuing utility scale solar development in the near future with the potential to export that energy to neighboring countries.

Chapter IV: Modeling of Concentrating Solar Power Plants in the Kingdom of Saudi Arabia

Modeling Set Up

The study's primary focus is to gain some insight in the prospects of integrating solar electric generation into Saudi Arabia's electricity mix. The approach of this study will be a series of scenarios with varying degrees of solar implementation. Each scenario will have a certain percentage of solar power needed in the total installed capacity with a deadline of 2020.

A total of four scenarios were used that are based on renewable portfolio standards. The first scenario is the base case, business as usual with no solar integration. The second scenario is a 5% total capacity sourced from concentrating solar power plants. The 5% scenario is based on a recent renewable energy initiative set by Kuwait, a neighboring country of Saudi Arabia (New Energy Finance, 2009). The third scenario consists of 10% of the total capacity sourced from CSP. The fourth scenario consists of a 15% scenario, and the fifth scenario is a 20% renewable portfolio standard. It is theorized that the upper limit of intermittent energy sources such as wind and solar power ranges between 15-30% of the total capacity, assuming current transmission and dispatchablility strategies and technologies (Grubb & Meyers, 1993). Another reason for a maximum of 20% is due to the issue of modeling and cost evaluation of thermal power generators that are used to generate electricity and water desalination. In these models, CSP plants will not replace any planned thermal plants that have the dual purpose of power generation and water desalinization, limiting the maximum CSP integration at 20%.

Microsoft Excel and the National Renewable Energy Laboratory's modeling software, Solar Advisor Model (SAM) are used for this study. SAM is used to model all of the performance and cost data of all of the power plants as well as used for sensitivity analysis. Outputs used from SAM are net present values (NPV) of each project, levelized cost of energy (LCOE), sensitivity analysis and total kilowatt-hour output throughout the lifespan. Excel is used to aggregate all of the project outputs for data analysis for each scenario.

Table 1 contains all future power plant construction in chronological order. These new constructions are used as the basis of all conventional power plants in each scenario. The base case scenario encompasses all of these power plants. Most of the steam plants in the table are used for both electricity generation and water desalinization. As mentioned before, these power plants will not be included in any NPV analysis due to the lack of cost and output data in respect to water desalinization for both conventional and CSP plants. The power plants in red are the power plants that are omitted, but they are included in the analysis of total future installed capacity.

Table 1: Planned Power Plant Installations

Project Name	Type	Capacity (mW)	Entering Service	Fuel	Price ($ U.S.)
Expansion of Qurayyah PP	Comb Cycle	1,905	2009	Natural Gas	$1,040,000,000
Expansion of PP 9	Single Cycle	480	2009	Natural gas	$221,866,667
Expansion of Faras PP	Single Cycle	480	2009	Natural Gas	$156,000,000
Expansion of Rabigh PP	Single Cycle	1,680	2009	Natural gas	$932,000,000
Private Sector: Jubail PP	Comb Cycle	2,600	2009	Natural Gas	$3,400,000,000
Private Sector: Al-Shoaiba PP	Steam	900	2009	Crude Oil	$2,450,000,000
Power Plant 10	Comb Cycle	2,000	2010	Natural Gas	$2,000,000,000
Private Sector: Al-Shuqaiq	Steam	850	2010	Crude Oil	$2,000,000,000
Expansion of Al-Shoaiba PP	Steam	1,200	2011	Crude Oil	$2,800,000,000
Ras Al-Zor PP	Steam	1,000	2012	Crude Oil	$5,500,000,000
Private Sector: Power Plant 11	Comb Cycle	2,000	2012	Natural Gas	$2,133,333,333
Private Sector: Rabigh PP	Steam	1,200	2012	Crude Oil	$1,333,333,333
Expansion of Qurayyah PP	Comb Cycle	1,255	2012	Natural Gas	$1,850,000,000
Expansion of Rabigh Steam PP	Steam	2,400	2012	Crude Oil	$4,000,000,000
Private Sector: Qurayyah PP	Steam	2,000	2014	Crude Oil	$2,133,333,333
Expansion of PP 10	Comb Cycle	990	2014	Natural Gas	$993,311,036
Shuqaiq PP	Steam	3,200	2014	Crude Oil	$6,400,000,000
Dhabaa Steam PP	Steam	1,000	2014	Crude Oil	$2,000,000,000
Ras Al-Zar PP	Steam	3,600	2015	Crude Oil	$7,200,000,000
South Jeddah PP	Steam	3,600	2015	Crude Oil	$7,200,000,000
Al-Uquair PP	Steam	3,600	2016	Crude Oil	$7,200,000,000

Cost and Technical Data

Table 2 contains the technical data needed for SAM. The heat rate data was sourced from the EIA website (Energy Information Administration, 2009). The capacity factors for each of the conventional power plants were sourced from the 2008 Saudi Electricity Company Annual Report (Saudi Electricity Company, 2009). The degradation rates were sourced from a report from the California Energy Commission (California Energy Commission, 2007). The economic timeline was also based on studies conducted by the CEC.

Table 2: Technical Data

Heat Rate (Btu/kWh)	
Combined Cycle	7445
Gas Turbine	11466
Crude Oil	10400
Capacity Factor	
Combined Cycle	0.7
Gas Turbine	0.48
Steam	0.7
Degradation Rate	
Combined Cycle	0.02
Gas Turbine	0.02
Economic Timeline	30 years

Table 3 contains all of the costs in regards to conventional power plants. The fuel costs were sourced from the Saudi Arabian Ministry of Foreign Affairs website (Ministry of Foreign Affairs, 2008). Both the fixed and variable costs for each of the conventional power plants used were sourced from the document, “Assumption to the Annual Energy Outlook 2009,” from the EIA (Energy Information Administration, 2009).

Table 3: Cost Data

Fuel Cost	
Natural Gas	$0.75/mmBTU
Crude Oil	$0.10/liter
Fixed Cost	
Combined Cycle	$12.46/kw-yr
Simple Cycle	$12.12/kw-yr
Thermal	$27.53/kw-yr
Variable Cost	
Combined Cycle	$2.07/mWh
Simple Cycle	$3.57/mWh
Thermal	$4.59/mWh

Table 4 contains the financial data needed for SAM. The depreciation rate and income tax were sourced from the Saudi Arabian tax law (Dept. of Zakat and Income Tax, 2009). The inflation rate and the interest rates were sourced from the CIA World Factbook (Central Intelligence Agency, 2009). A 5% real discount rate was selected due to the use of this number in several renewable energy research papers (Trieb, et al., 2005)(Frisvold, Patton, & Reynolds, 2009)(Stoddard, Abiucunas, & O'Connell, 2006). Debt ratios were sourced from several project finance reports for many of Saudi Arabia's power plant construction. Most of the projects had an 80% debt ratio and several others had 60% debt ratios. To simplify, the debt ratio of 80% was used as a proxy for all of the power plant construction costs for both conventional and CSP power plants.

Table 4: Financial Data

Depreciation		Length
Gas and Oil Power	Straight Line	27 yrs
Income Tax	20%	
Inflation Rate	4%	
Real Discount Rate	5%	
Debt Ratio	80%	
Central Bank Interest Rate	6.00%	

Table 5 contains the cost and technical data needed to run simulations for the trough CSP plants in SAM. The data in the table were sourced from (Sargent & Lundy, 2003). The Sargent & Lundy study assumes CSP evolutions at 2007, 2010 and 2015 with increased capacity at 100 MW, 150 MW and 200 MW respectively. All other necessary inputs within SAM were left at the default settings in the following sections of SAM; Solar Field, Solar Collector Field/ Heat Collection Element, Power Block, Thermal Storage, and Parasitics.

Table 5: CSP Cost and Technical Data

	Trough 100 (2007)	Trough 150 (2010)	Trough 200 (2015)
Heat Transfer Fluid System			
HTF Type	HiTec XL	Hitec XL	Hitec XL
Fluid Volume, gallons	637,560	907,830	1,201,200
Hours of Thermal Storage	6	6	6
Direct Capital Cost	$294,929,000	$373,033,000	$439,654,000
Fixed Cost by Capacity	$50/kW-yr	$50/kW-yr	$50/kW-yr

Power Plant Results

Using SAM, all of the power plant NPV's and LCOE's were calculated which are displayed in Table 6. The numbers in red depict a negative NPV. The table is ordered from the highest NPV to the lowest. The CSP plants are separated from the conventional power plants. Due to the high cost per watt, all of the CSP plants have negative NPV's and have the highest LCOE. It should be noted that the LCOE goes down in conjunction to each evolution of the trough CSP but it does not meet parity to the LCOE of the other conventional power plants.

All of the steam power plants have negative NPV's as well as all of the private sector power plants. The private sector power plants are part of a new program by the SEC of implementing independent power plants. Each of the private sector plants has a 1% escalation rate for the power purchasing agreements adding to the negative NPV's. The power plants with the highest NPV are publically owned combined cycle power plants.

As expected any power plants with an LCOE greater than the Saudi Arabian electric tariff rate of 3 cents per kilowatt-hour, with exception to the expansion of power plant 9, has a negative NPV.

Table 6: Power Plant NPV's and LCOE Calculations

Project Name	Type	MW	Project Cost	NPV	LCOE (nom) in U.S. cents
Expansion of Qurayyah PP	Comb Cycle	1255	$1,850,000,000	$620,619,101	1.88
Power Plant 10	Comb Cycle	2000	$2,000,000,000	$609,951,856	1.90
Expansion of Qurayyah PP	Comb Cycle	1905	$1,040,000,000	$532,899,185	1.92
Expansion of PP 10	Comb Cycle	990	$993,311,036	$293,643,192	1.91
Expansion of Rabigh Power Plant	Single Cycle	1680	$932,000,000	$142,762,279	2.14
Expansion of Faras Power Plant	Single Cycle	480	$156,000,000	$130,534,625	1.78
Expansion of Power Plant 9	Single Cycle	480	$221,866,666	$77,565,163	1.99
PrSec: Rabigh Power Plant	Steam	1200	$1,333,333,333	$568,069,676	3.42
PrSec: Power Plant 11	Comb Cycle	2000	$2,133,333,333	$909,296,635	3.94
Expansion of Rabigh Steam PP	Steam	2400	$4,000,000,000	$1,049,165,000	4.35
PrSec: Qurayyah Power Plant	Steam	2000	$2,133,333,333	$1,620,968,949	4.49
PrSec: Jubail	Comb Cycle	2600	$3,400,000,000	$1,856,251,207	4.55
CSP 2007	CSP	100	$331,176,065	$193,573,831	9.11
CSP 2010	CSP	150	$444,266,849	$215,633,072	8.03
CSP 2015	CSP	200	$611,011,793	$291,470,421	7.93

Scenario Set Up

Using the power plant NPV's that were calculated from SAM (Table 6), the NPV's of each scenario are then calculated. For scenarios that have CSP integration, conventional power plants with negative NPV's are replaced with the equivalent amount of CSP plants, starting with the conventional power plants with the greatest negative NPV.

In order to ensure additional installed capacity meets annual power demands, there needs to be a deployment strategy that does not create a power capacity demand deficit. Therefore, each scenario is cross-referenced with expected demand to ensure that the installed capacity is equal or greater than the expected demand. The bottom two rows, Net Cumulative Capacity and Expected Demand, on the tables below illustrate this.

Table 7: Business As Usual Scenario with No CSP Deployment

(Gigawatts)	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Total Installed Capacity/year	8.05	2.85	1.20	7.86	0.00	7.19	7.20	3.60	0.00	0.00	0.00	0.00
Net Cumulative Capacity	47.25	50.10	51.30	59.15	59.15	66.34	73.54	77.14	77.14	77.14	77.14	77.14
Expected Demand	41			50.1			59.5			68.2		75.1

Table 8: 5% Scenario & Annual CSP Deployment

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
CSP Technology													
100 MW(2007)	2	1											3
150 MW(2010)		2	2	2	2	2							10
200 MW(2015)							2	2	2	2	3	3	14
CSP Installed Capacity	0.2	0.4	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.6	0.6	
Total Installed Capacity/year	5.645	3.25	1.5	8.155	0.3	5.49	7.6	4	0.4	0.4	0.6	0.6	
Net CSP Installation	0.2	0.6	0.9	1.2	1.5	1.8	2.2	2.6	3	3.4	4	4.6	
Net Cumulative Capacity	44.845	48.095	49.595	57.75	58.05	63.54	71.14	75.14	75.54	75.94	76.54	77.14	
Expected Demand	41			50.1			59.5			68.2		75.1	

The following power plants were replaced with CSP plants for the 5% scenario:

- PrSec: Jubail (NPV: -$1,856,251,206)
- PrSec: Qurayyah Power Plant (-$1,620,968,948)

Table 9: 10% Scenario & Annual CSP Deployment

(Gigawatts)	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
CSP Technology													
100 MW(2007)	2												2
150 MW(2010)		2	3	3	3	5							16
200 MW(2015)							2	3	3	4	5	5	22
CSP Installed Capacity	0.2	0.3	0.45	0.45	0.45	0.75	0.4	0.6	0.6	0.8	1	1	
Total Installed Capacity/year	5.645	3.15	1.65	5.905	0.45	5.94	7.6	4.2	0.6	0.8	1	1	
Net CSP Installation	0.2	0.5	0.95	1.4	1.85	2.6	3	3.6	4.2	5	6	7	
Net Cumulative Capacity	44.845	47.995	49.645	55.55	56	61.94	69.54	73.74	74.34	75.14	76.14	77.14	
Expected Demand	41			50.1			59.5			68.2		75.1	

The following power plants were replaced with CSP plants for the 10% scenario:

- PrSec: Jubail (NPV: -$1,856,251,206)
- PrSec: Qurayyah Power Plant (-$1,620,968,948)
- Expansion of Rabigh Steam PP (-$1,049,165,000)

Table 10: 15% Scenario & Annual CSP Deployment

(Gigawatts)	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
CSP Technology													
100 MW (2007)	2												2
150 MW (2010)		4	4	4	5	6							23
200 MW (2015)							5	5	5	7	8	8	38
CSP Installed Capacity	0.2	0.6	0.6	0.6	0.75	0.9	1	1	1	1.4	1.6	1.6	
Total New Installed Capacity	5.645	3.45	1.8	2.855	0.75	5.1	8.2	4.6	1	1.4	1.6	1.6	
Net CSP Installation	0.2	0.8	1.4	2	2.75	3.65	4.65	5.65	6.65	8.05	9.65	11.25	
Net Cumalative Capacity	44.845	48.295	50.095	52.95	53.7	58.8	67	71.6	72.6	74	75.6	77.2	
Expected Demand	41			50.1			59.5			68.2		75.1	

The following power plants were replaced with CSP plants for the 10% scenario:

- PrSec: Jubail (NPV: -$1,856,251,206)
- PrSec: Qurayyah Power Plant (NPV: -$1,620,968,948)
- Expansion of Rabigh Steam Power Plant (NPV: -$1,049,165,000)

- PrSec: Power Plant 11 (NPV: -$909,296,634)
- PrSec: Rabigh Power Plant (NPV: -$568,069,675)
- Expansion of Power Plant 10 (NPV: $293,643,192)

Table 11: 20% Scenario & Annual CSP Deployment

(Gigawatts)	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
CSP Technology													
100 MW (2007)	3												3
150 MW (2010)		4	6	7	9	10							36
200 MW (2015)							6	7	8	9	10	12	52
CSP Installed Capacity	0.3	0.6	0.9	1.05	1.35	1.5	1.2	1.4	1.6	1.8	2	2.4	
FF & CSP Installed Capacity	4.065	1.45	2.1	2.05	1.35	5.7	8.4	5	1.6	1.8	2	2.4	
Net CSP Installation	0.3	0.9	1.8	2.85	4.2	5.7	6.9	8.3	9.9	11.7	13.7	16.1	
Net Cumalative Capacity	43.265	44.715	46.815	48.865	50.215	55.915	64.315	69.315	70.915	72.715	74.715	77.115	
Expected Demand	41			50.1			59.5			68.2		75.1	

The following power plants were replaced with CSP plants for the 10% scenario:

- PrSec: Jubail (NPV: -$1,856,251,206)
- PrSec: Qurayyah Power Plant (NPV: -$1,620,968,948)
- Expansion of Rabigh Steam Power Plant (NPV: -$1,049,165,000)
- Expansion of Rabigh Single Cycle Power Plant (NPV: $142,762,279)
- PrSec: Power Plant 11 (NPV: -$909,296,634)
- PrSec: Rabigh Power Plant (NPV: -$568,069,675)
- Expansion of Power Plant 10 (NPV: $293,643,192)
- Power Plant 10 (NPV: $609,951,856)

Results of the Scenarios

The NPV's for each scenario were calculated and are shown in Figure 11. All of the scenarios have negative NPV's, including the business as usual scenario, with an NPV of -$2.7 billion. The 5% and 10% NPV are -$4.489 billion and -$4.801 billion respectively. The difference between the two scenarios is $312,000,000. Yet, the difference between the 10% and the 15% scenario is $2.376 billion. The 20% scenario has an NPV of -$10.424 billion, a jump of -$4.691 billion from the 15% scenario.

It should be noted that these NPV's do not include any CSP financial incentives or subsidies. It also should be noted that the NPV's for the conventional power plants have inbuilt direct and indirect subsidies which are mainly from subsidized feedstock as well as subsidized electric tariff rates (The Economist, 2009)(Energy Information Administration, 2008).

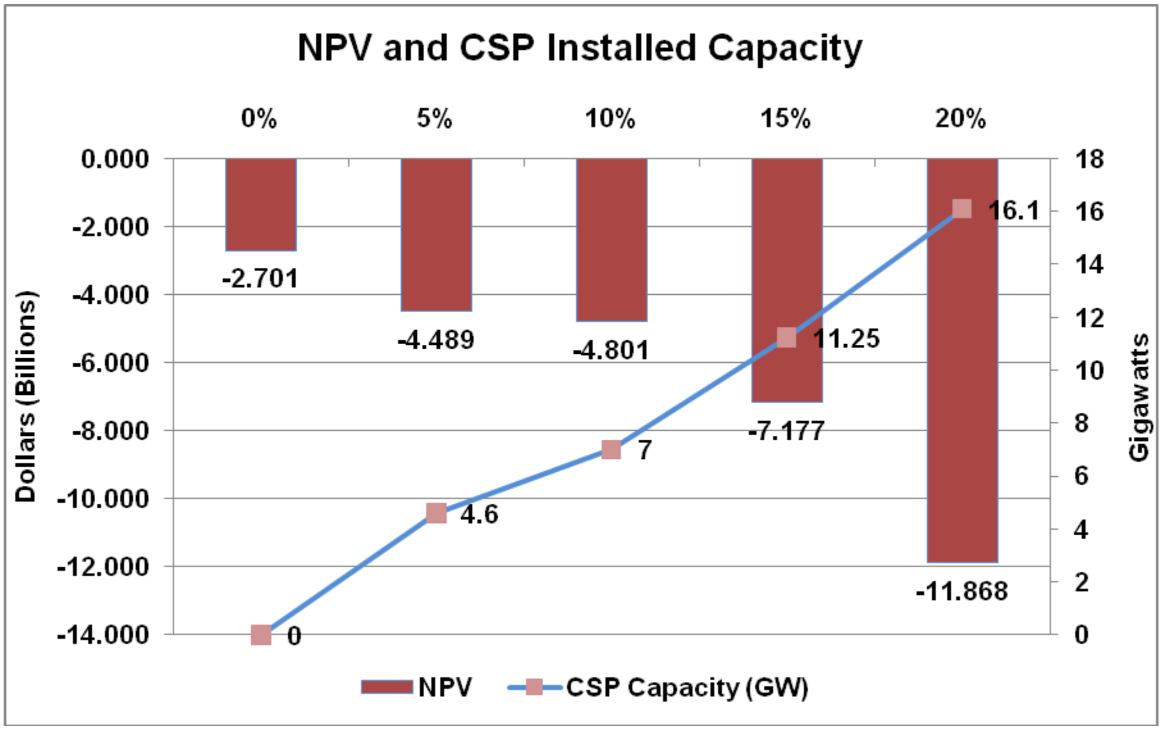


Figure 11: NPV and CSP Installed Capacity

Chapter V: Unsubsidized vs. Consumer Cost Increase NPV Analysis

Unsubsidized CSP Scenario Selection

This section will help dictate which CSP scenario should be used for the rest of the study in terms of unsubsidized NPV's. To see which scenario is the most cost effective, the NPV of each scenario is divided by the total CSP capacity of the respective scenario. The figures in bullet points below are the calculated NPV dollars per gigawatt. It should be noted that the NPV calculations include all conventional and CSP installations.

- **5% Scenario: -$0.976 billion/GW**
- **10% Scenario: -$0.686 billion/GW**
- **15% Scenario: -$0.638 billion/GW**
- **20% Scenario: -$1.41 billion/GW**

Using this calculation, the 20% scenario has the greatest negative NPV per Gigawatt of CSP installed. This primary reason for this is due to the elimination of conventional power plants with positive NPV's, including the Expansion of Power Plant 10 (NPV: $293,643,192) and Expansion of Rabigh Single Cycle Power Plant (NPV: $142,762,279). The 20% scenario also has a total of 91 individual CSP power plants; most coming from the third generation 200 MW CSP plants totaling 52.

The 10% and 20% scenario have the least negative NPVs per gigawatt of CSP installed capacity ratio in relation to the other two scenarios. Similar reasons why the 20% has the highest ratio, the 10% and 15% scenario eliminates most of the conventional power plants with the greatest negative NPV's.

In this regards, the 10% or 15% scenario would be one of the better scenarios to pursue, should Saudi Arabia pursue solar integration. This scenario would provide the country with the best "bang for your buck," albeit a negative "bang for your buck." If the country puts more weight on NPV's, the 10% scenario would probably be picked due to the overall favorable NPV versus the 15%.

Current Electricity Subsidies

As mentioned previously, subsidies were included in all of the conventional power plant NPV's and LCOE's. It is relatively unknown how much the electric industry is subsidized. This includes the price of natural gas being sold at $0.75/mmBTU since the early 1990's, as well as the average electricity tariff rate being at $0.03/kWh. These two price points being stable over the past decade is a clear indication of government subsidies being used.

According to a study conducted by the International Energy Association, in the year 2007, approximately $25 billion in government subsidies were used for the energy industry which includes the electricity utility (The Economist, 2009). This number equates to about $1,036 per capita.

Even with government subsidies, the business as usual model indicates an overall negative NPV for new installed capacity, which can be seen as a reflection of a recorded loss of $205.6 million in the first quarter of 2008 from the Saudi Electric Company (Maree, 2009). This is SEC's biggest loss in the last four years. This is due to the increase demand of electricity per capita. As people become more affluent, quality of life increases along with an increase in energy demand. This includes people buying larger houses, which create a greater load from air conditioning units.

Therefore, it is unfair to compare subsidized conventional power plants with unsubsidized CSP plants. The issue at hand is figuring out the true cost of electricity and feedstock, mainly natural gas and crude oil. Since the electric utility and oil industry are vertically integrated and government owned, reliable information relating to subsidies is difficult to obtain.

Subsidized electricity with a growing population and GDP, is becoming a large concern and meeting this growing demand with current government subsidies is creating a capital strain. Assuming the business as usual model is correct with the negative NPV, and with a difference of $1.788 billion and $2.1 billion respectively to the 5% and 10% scenario, there needs to be mechanism that would help reduce the NPV's of the 10% scenario.

Electric Tariff Increase

As mentioned before, subsidies riddle the electric utility. The primary concern in implementing CSP into the electric mix is the financial burden the Kingdom will bear on top of the current utility environment. Therefore, should CSP implementation occur, some of that burden could be transferred to the consumers as slightly higher electric tariff rates. With the average cost of electricity at $0.03 per kilowatt-hour, a slight increase in the tariff rate on the surface should not be a large burden to the citizens.

It should be noted that the electricity tariff rate is not a flat rate of $0.03 per kilowatt-hour; it is simply an average derived from the annual reports released from the SEC. It is a calculation of revenue from electricity sold divided by the total kilowatt-hours sold. Table 11 breaks down the electricity tariff structure (Ministry of Foreign Affairs, 2008). Unfortunately, information in regards to the exact revenue from each sector and rates charged was not obtained and is not readily accessible to the public.

Table 12: Monthly Power Tariff Rates

Consumer Type/Use	Tariff
Industrial	
Any Volume of Usage	$0.032
Agricultural	
1-2,000 kWh per month	$0.013
2,001-5,000 kWh per month	$0.026
Over 5,000 kWh per month	$0.032
Commercial, Residential and Governmental	
2,000 kWh per month	$0.013
2,001-4,000 kWh per month	$0.026
4,001-6,000 kWh per month	$0.032
6,001-7,000 kWh per month	$0.040
7,001-8,000 kWh per month	$0.053
8,001-9,000 kWh per month	$0.059
9,001-10,000 kWh per month	$0.064
Over 10,000 kWh per month	$0.070

Due to the fact that exact information of the tariff rates charged was not obtained, the average cost increase will be calculated. The primary purpose of the following calculations is to establish a range of the average tariff rates using the 5 scenarios (baseline, 5%, 10%, 15%, 20%), including the CSP deployment schedule (Table 9).

The following are needed to calculate the average increased tariff rate with CSP deployment.

- The real levelized cost of energy of each type of CSP plants.
- Cost of electricity from conventional sources is $0.0300/kWh.
- Expected electricity consumption from 2009 to 2030.
- Annual electricity generation from CSP plants.

Figure 5, depicts the expected electricity capacity and consumption up to 2020. Unfortunately, the study only analyzes the following years, 2012, 2015, 2018 and 2020 (Saudi Electricity Company, 2009). In order to obtain the figures for the other years, a regression analysis is needed. Using Microsoft Excel, an exponential regression was calculated, $y=83.006e^{0.0547x}$, $R^2=0.99637$. The new historical and expected annual electricity consumption can be seen in Figure 12.

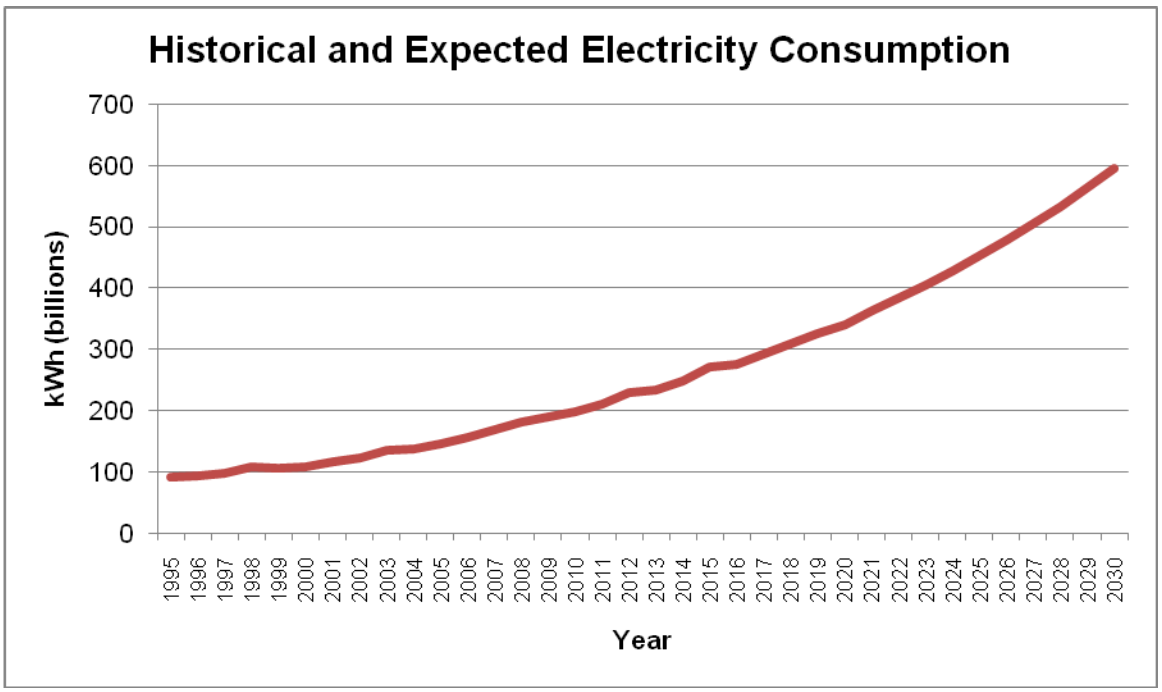


Figure 12: Historical: 1995-2008 , Expected: 2009-2030

The real levelized cost of energy is used as the selling price of the CSP plants (Table 12). Along with the deployment schedules in Tables 9, 10 and 11, Table 13 contains all of the necessary CSP information needed to calculate the average tariff rate as well as the updated NPV's with respect to the CSP selling price (Real LCOE).

Table 13: CSP LCOE and NPV Calculations

CSP Type	Real LCOE ($)	NPV	Annual kWh
100mW	0.0577	-75,240,075	362,657,176
150mW	0.0508	-92,192,905	503,802,781
200mW	0.0502	-125,664,314	696,813,487

Figure 13 contains the calculated average of each scenario. The timeline goes to 2030 but the CSP construction ceases in 2020. In the figure below, the average price peaks at 2020 and after that year, the average cost goes down since there is no increase in CSP power production, while power consumption continues to go up. The 20% scenario peaks at $0.0334/kWh, a difference of 1/3 of a cent ($0.0034/kWh) compared to the baseline scenario.

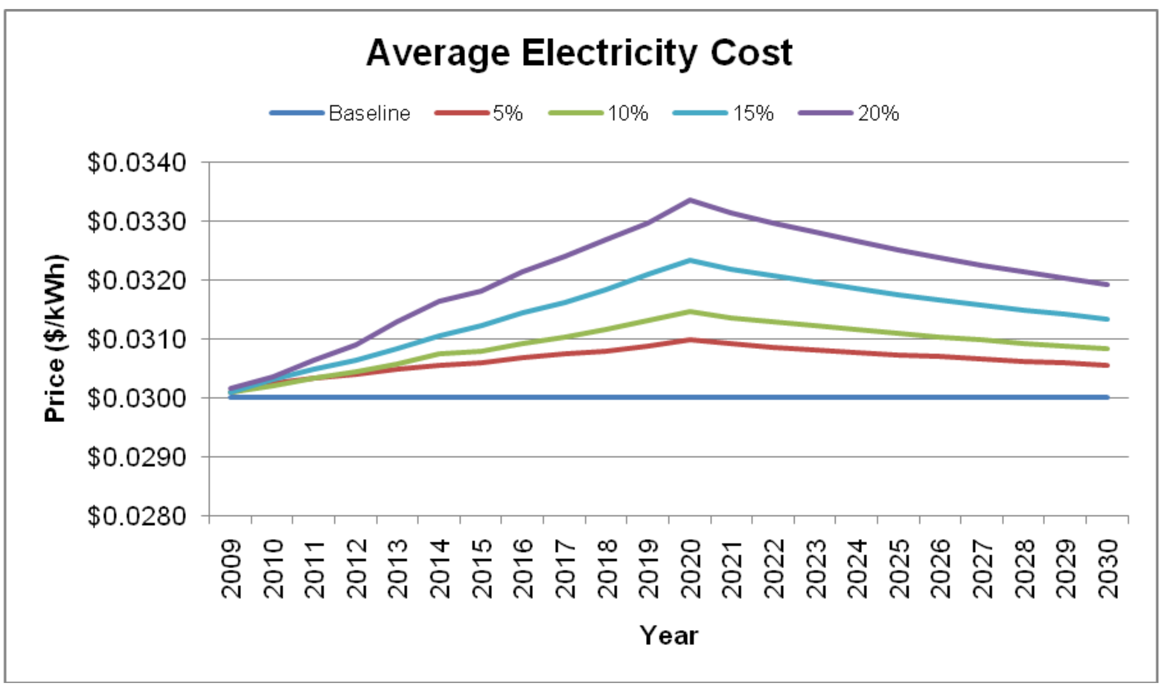


Figure 13: Average Electricity Cost

Once the LCOE is used as the selling price of the CSP plants, the NPV's of the plants are reduced (Table 13), which in turn drastically alters the NPV's of each scenario. Figure 14 depicts the recalculated NPV's of each scenario. All of the scenarios still have a negative NPV but the CSP NPV's are drastically reduced, once the financial burden is shifted to the consumer, through higher electricity cost.

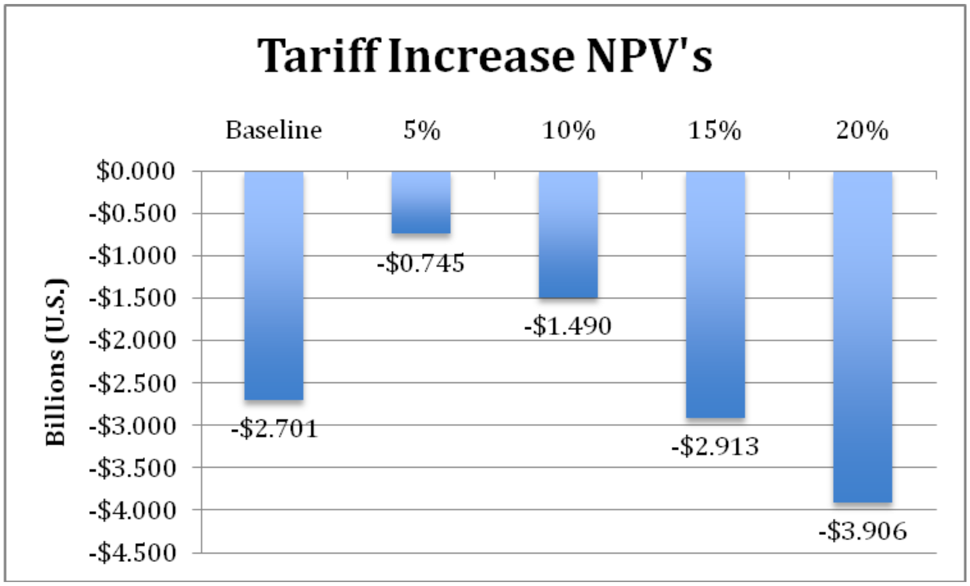


Figure 14: Tariff Increase NPV's

The 5% and 10% scenarios are more favorable than the baseline, while the 15% and 20% scenarios have a greater negative NPV. The 15% scenario is the closest to the baseline with an NPV difference of $212 million. The reason for the favorable NPV's with CSP integration is due to the tariff increase structure as well as eliminating some of the costly conventional power plants in terms of NPV.

Since the some of the financial burden has shifted to the consumer, it is necessary to assess the cost burden. As seen before, the difference between the average cost of electricity at the peak (2020) between the 20% and the baseline scenario is an increase of 1/3 of a cent per kilowatt-hour. According to the United Nations Population Database, the population of Saudi Arabia will be 31,608,000 (medium variant) by 2020 (United Nations, 2009). Using the expected population by 2020, the electricity cost per capita can be calculated for that peak year, which is depicted in Figure 15. The baseline has a cost per capita of $322.47. The greatest increase in terms of cost per capita is the 20% scenario at $358.52, a difference of 10% increase from baseline.

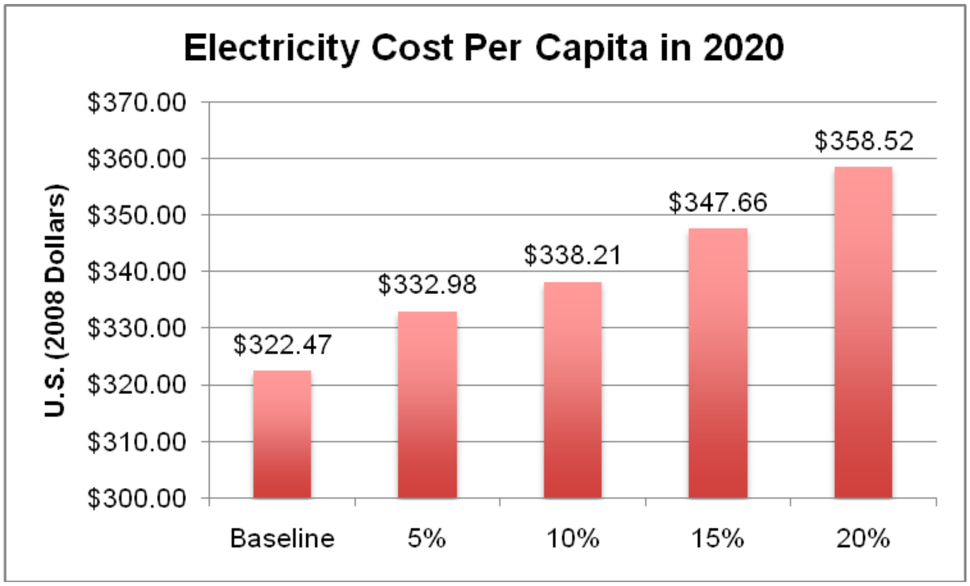


Figure 15: Electricity Cost Per Capita in 2020

Electric Tariff Increase Scenario Selection

In the previous case, with no solar subsidies, the baseline scenario was the most favorable at a cost advantage. But should the government not alter the pricing structure, the cost of solar implementation is costly as can be seen in Figure 11. But once that financial burden is shared between the government and its citizens, solar implementation becomes more favorable. Figures 13 and 15 shed some light in regards to how much of that financial cost is shifted.

Analyzing the 20% scenario, there is an increase of 1/3 of a cent per kilowatt-hour in the year 2020, the greatest increase in this scenario. In regards to electricity cost per capita, there is a 10% increase from the baseline to the 20% scenario. These cost increases are not too drastic, but it is relative. There needs to be further analysis on the economic impact of these increase electricity costs. At least on the surface, the cost increase most likely will not create a drastic financial burden to the consumers. But looking at the viewpoint of the Saudi government, the NPV of the scenario is not favorable in relation to the baseline scenario, with a difference in NPV at -$1.205 billion. This is with the assumption that the selling price of CSP power generation is sold at the LCOE of each power plant.

The best compromise in regards to the consumer and government would be the 15% scenario. From the viewpoint of the Saudi government, the NPV of the 15% scenario and the Baseline scenario are very similar, with the difference of -$212 million (8% difference in NPV). From the viewpoint of the consumer, there would be a maximum average real price of $0.0323, a ¼ of a cent increase from the baseline price. From the an energy cost per capita in the year 2020, there would be an increase of $25 per capita, a difference of 8%.

If the primary goal for the Kingdom of Saudi Arabia is to maximize solar integration without compromising the country's financial burden in relation to the business as usual scenario, the 15% scenario tariff increase would be the ideal choice. This is due to the similar NPV numbers between the two scenarios.

As mentioned, the prices ($/kWh) are averaged and as can be seen in Table 12, there is a tariff rate pricing system that escalates as more power is consumed. Therefore, there needs to be a thorough analysis of the revenue breakdown in regards to the tariff rate pricing system. Along with this, there needs to be an analysis of the economic and purchasing power of the different consumers. It may be a good idea to prevent a financial burden on low-income citizens and businesses, while increasing the tariff rates at the higher end of the pricing bracket, targeting residential and commercial customers that are able to afford the increased tariff rates. Since the tariff pricing system has increasing tariff rates as consumption goes up, increasing the price at the high consumption levels while keeping the tariff rates at the low consumption levels would be a good starting point. This may in turn also promote energy efficiency and smarter electricity management, reducing energy waste.

Chapter VI: Fossil Fuel Consumption

Domestic Natural Gas Dilemma and Forecasted Consumption

As mentioned previously, Saudi Arabia is currently encountering natural gas supply issues, with shortages due to the inability to meet demand. This is primarily due to most of the natural gas being produced from associated oil reservoirs. Due to domestic and OPEC production quotas, the production schedule of crude oil does not coincide with the natural gas demand, creating a bottleneck in natural gas production. This has led to the increasing use of crude oil as feedstock for electricity production, thus cannibalizing some of the potential revenue produced from exporting the crude oil. As previously stated, natural gas is not exported or imported from Saudi Arabia. It is strictly used for domestic consumption. Saudi Aramco is currently under pressure to place more effort on natural gas exploration after the 2004 non-associated natural gas exploration initiative in the Rub Al-Khali proved unsuccessful. Currently, due to the low domestic price of natural gas and high cost of extraction, there is little incentive for international oil companies to get involved (Middle East Economic Digest, 2009).

In this study, 5 scenarios are used; baseline, 5%, 10%, 15% and 20% CSP integration. It is suggested that integrating CSP plants could reduce natural gas demand. If there is a reduction in natural gas demand, several power plants running on crude oil could be switched to run on natural gas, thus freeing up crude oil to be exported.

In this section, each scenario will be analyzed in respect to natural gas consumption and will be analyzed in the overall reduction in natural gas demand. It should be noted that since CSP power plants in this study do not directly replace steam powered cogeneration power/water desalination plants, they are omitted from this section.

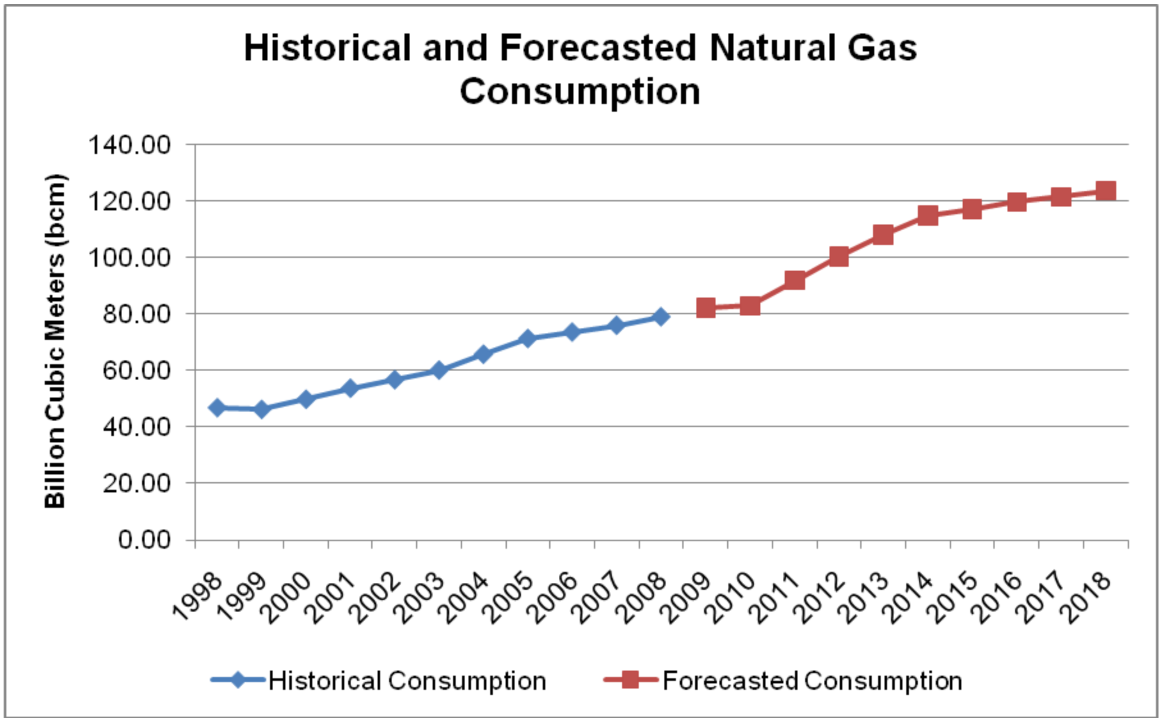


Figure 16: Historical and Forecasted Natural Gas Consumption

Figure 16 is a graph containing the historical and the forecasted consumption of natural gas in Saudi Arabia (Energy Information Administration, 2008)(Business Monitor International Ltd., 2009). As can be seen, there is a general expected decline in growth rate in natural gas consumption. This is in large part to switching to crude oil for feedstock over natural gas, due to production issues.

CSP Scenario Results on Net Fossil Fuel Feedstock Reduction

The effects of CSP integration on net total fossil fuel feedstock consumption were calculated by estimating the expected yearly output of each conventional power plant throughout the power plant's lifetime. With each scenario, CSP plants replace planned conventional power plant construction. It is assumed that the overall kilowatt-hour produced from the displaced conventional power plants are produced from CSP plants. Therefore, as CSP plants are replacing more conventional power plants, there is an overall reduction in power output from conventional power plants for each scenario. Knowing the heat rate factor of the three types of conventional power plants used as well as the power produced the net consumption of crude oil and natural gas feedstock can be calculated for each scenario.

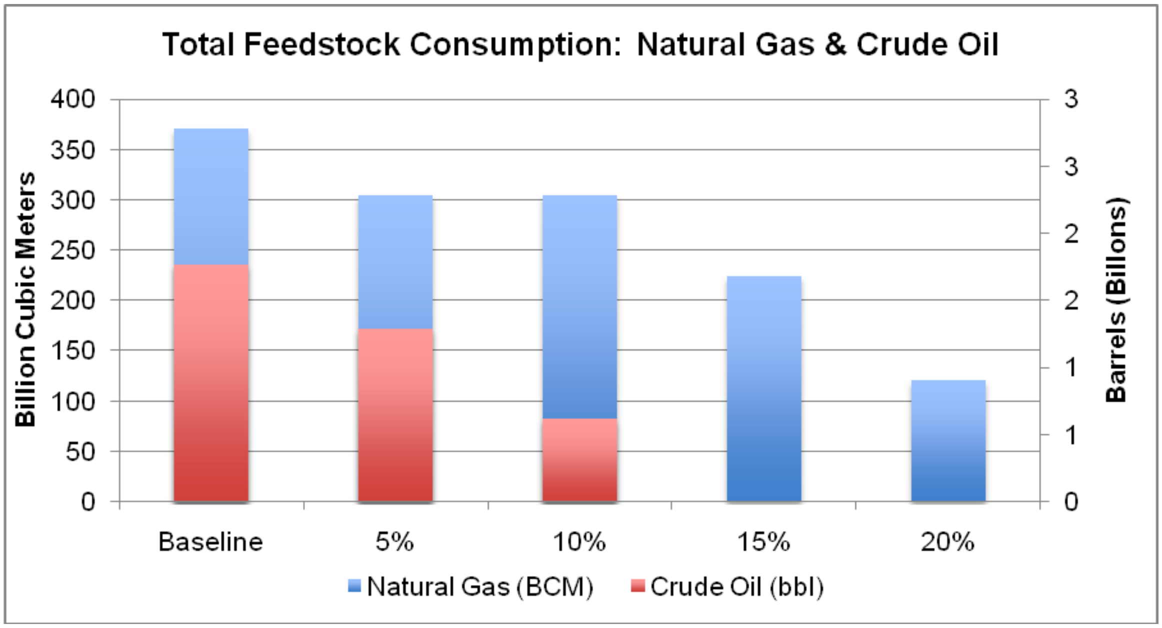
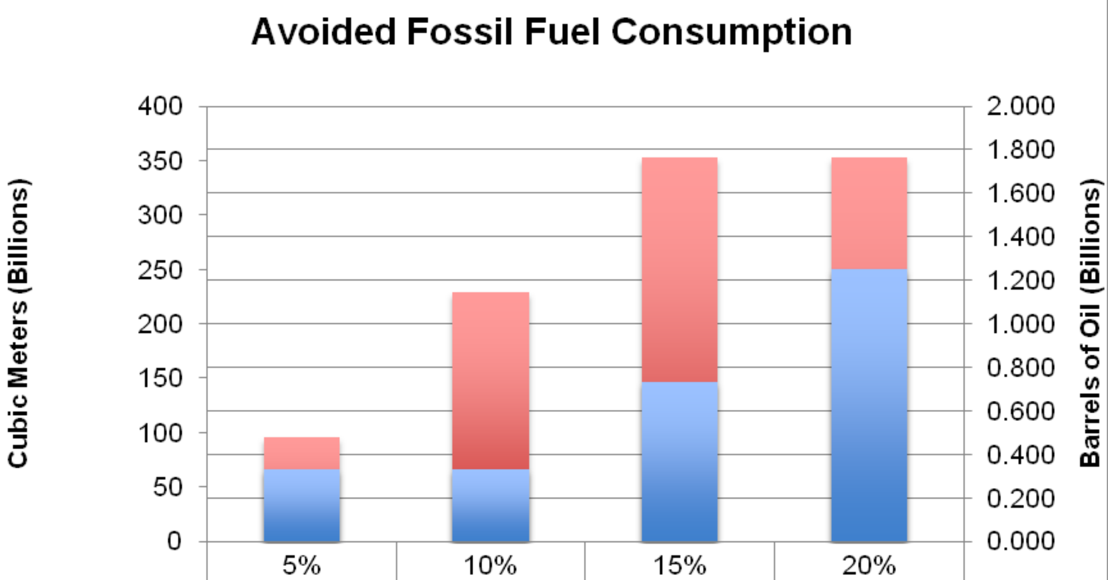


Figure 17: Total feedstock consumption: Natural gas & crude oil

Figure 17 depicts the total amount of fossil fuel feedstock used, both natural gas and crude oil for each scenario over the lifetime of all of the conventional power plants. Scenarios 15% and 20% have no crude oil consumption because CSP plants replaced all of the crude oil power plants. This should not be mistaken with CSP replacing all of the new crude oil thermal power plants. Overall, there is a clear decline in fossil fuel consumption as there is an increase in CSP integration. Scenarios 5% and 10% consumes the same amount of natural gas. This is due to the fact that no additional natural gas power plants were replaced in the 10% scenario. Instead, a crude oil power plant was replaced, as can be seen with the decrease in crude oil consumption.

In order to get a better understanding of how fossil fuels are being conserved, Figure 18 was constructed to depict the total avoided consumption of fossil fuels in each scenario by subtracting total consumption of fossil fuels in each scenario by the total consumption of fossil fuels in the baseline scenario. In the 15% and 20% scenario, about 1.8 billion barrels of crude oil was avoided, when all of the crude oil thermal power plants in the scenarios were eliminated. The 20% scenario avoided 250 billion cubic meters of natural gas while the 15% scenario avoided 146 billion cubic meters of natural gas.



	5%	10%	15%	20%
Crude Oil	0.476	1.146	1.765	1.765
Natural Gas	66	66	146	250

Figure 18: Avoided fossil fuel consumption

Knowing the amount of crude oil avoided, it is possible to monetize the money saved in real terms. In this case, the crude oil not used in these scenarios can be used for export rather being used as feedstock for electricity production. Figure 19 monetizes the total barrels of crude oil saved for each scenario with a set price of crude oil ranging from $50 per barrel to $150 per barrel of crude oil. Should the price of oil be at $150 per barrel and all of the crude oil was sold at once, Saudi Arabia would have sold about $265 billion worth of crude oil. Currently (late 2009), the price of oil is ranging around $75 per barrel of oil. Should the country implement solar energy with either a 15% or 20% scenario, the country has the potential of saving $132 billion from the barrels of crude oil avoided.

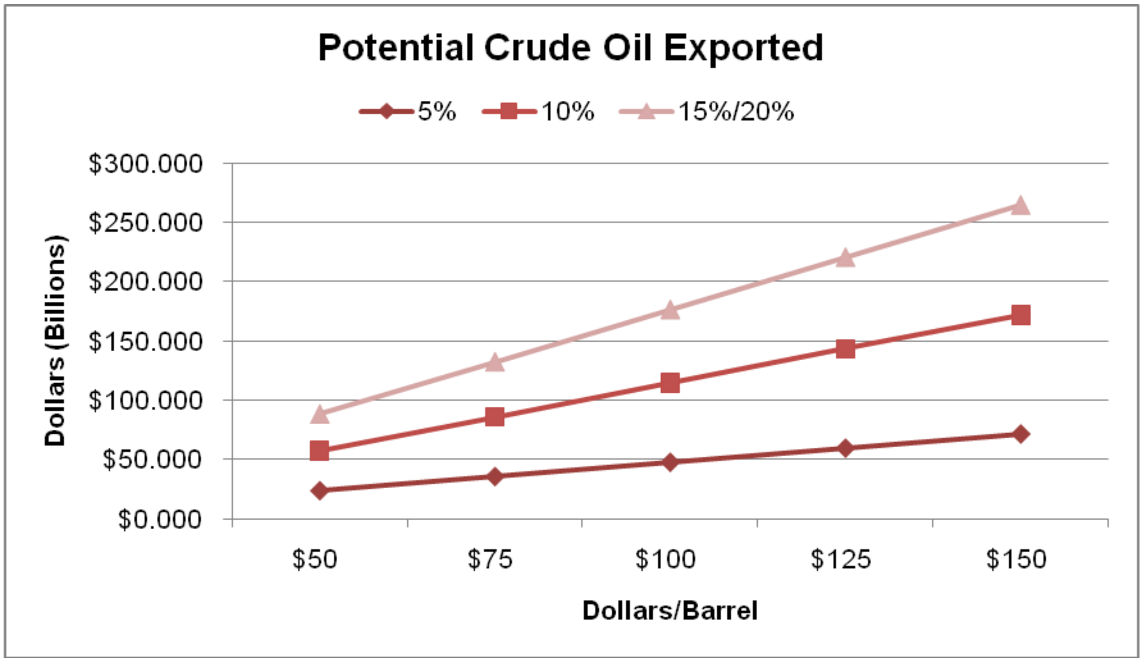


Figure 19: Potential crude oil exported

For comparison, Table 14 contains the construction cost of all CSP plants in each scenario. As can be seen, in terms of construction cost, the potential crude oil exported far outweighs the construction cost burden of each scenario, even if the cost of crude oil is at $50 per barrel. But, as shown before, the overall NPV's of each scenario are still negative and provide a greater financial burden on the electric utility if there is no increase in electricity tariffs.

Table 14: Construction Cost of CSP Plants

CSP Plant	Cost/Plant	5%	10%	15%	20%
100 mW	$331,176,065	$993,528,195	$662,352,130	$662,352,130	$993,528,195
150 mW	$444,266,849	$4,442,668,490	$7,108,269,584	$10,218,137,527	$15,993,606,564
200 mW	$611,011,793	$8,554,165,102	$13,442,259,446	$23,218,448,134	$31,772,613,236
	Total	*$13,990,361,787*	*$21,212,881,160*	*$34,098,937,791*	*$48,759,747,995*

The previous analysis separates natural gas and crude oil feedstock. Figure 20 aggregates both feedstocks into overall Btu's. This provides a better understanding of the overall impact CSP integration has on both natural gas and crude oil feedstock utilization. Figure 20 depicts three key points. The first is the total capacity of conventional electricity sources in each scenario. The second is the total capacity of

CSP plants in each scenario and the third key point is the overall fuel consumption of each scenario in quadrillion Btu's. As expected there as more CSP plants are being integrated, there is a direct reduction in fossil fuel feedstock consumption.

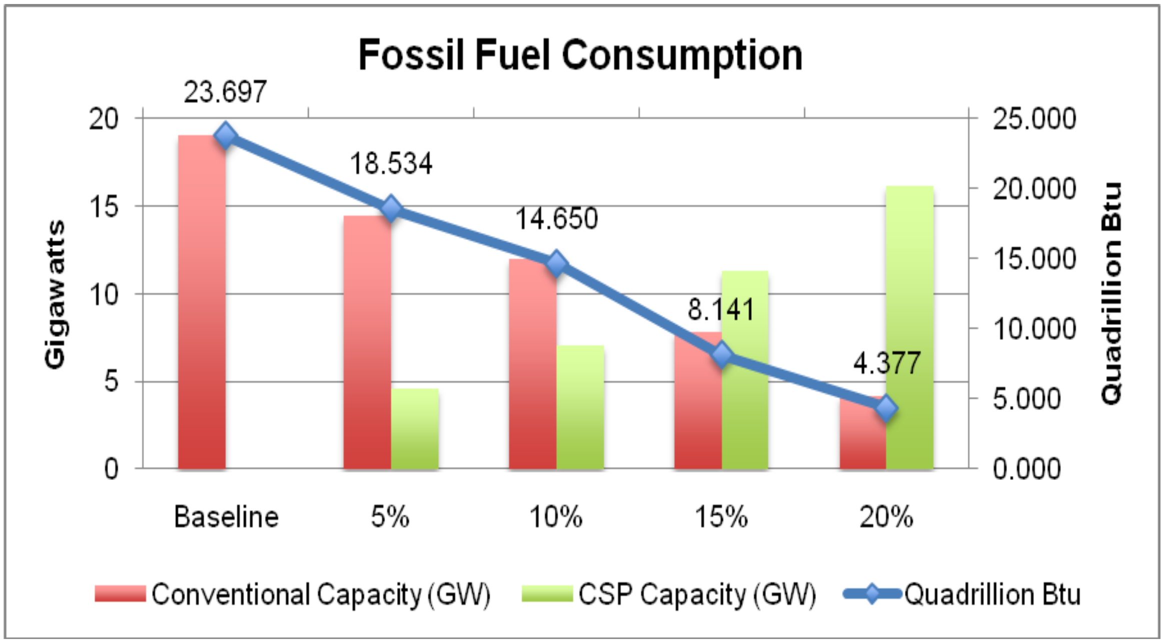


Figure 20: Fossil fuel consumption

CSP Scenario Results on Impact of Natural Gas Demand

With the current natural gas production issues, CSP integration could provide a supply relief. The question is how much of an impact CSP integration has on forecasted natural gas demand. Figure 16 contains the historic and forecasted natural gas demand. The yearly consumption of natural gas consumption of each scenario was calculated up to the year 2018. The reason for 2018 is due to the forecasted natural gas demand was only calculated up to that year. It should be noted that it is assumed that the baseline scenario does not alter the forecasted natural gas consumption.

Using the total kilowatt-hour output per year for each year and scenario, the amount of natural gas avoided was calculated by subtracting the natural gas consumed from each scenario against the base case scenario. The total avoided natural gas is then subtracted from the forecasted natural gas consumption. Figure 21 contains the new forecasted natural gas consumption, which includes all natural gas consumption from both the industrial and electricity sectors. Note that the 5% and 10% scenarios have the same natural gas consumption. This is due to the fact that both scenarios offset the same planned natural gas power plants. As can be seen there is a drop in natural gas consumption as more CSP plants are being integrated. In the final year, there is a gap of 10 billion cubic meters between the baseline scenario and the 20% scenario.

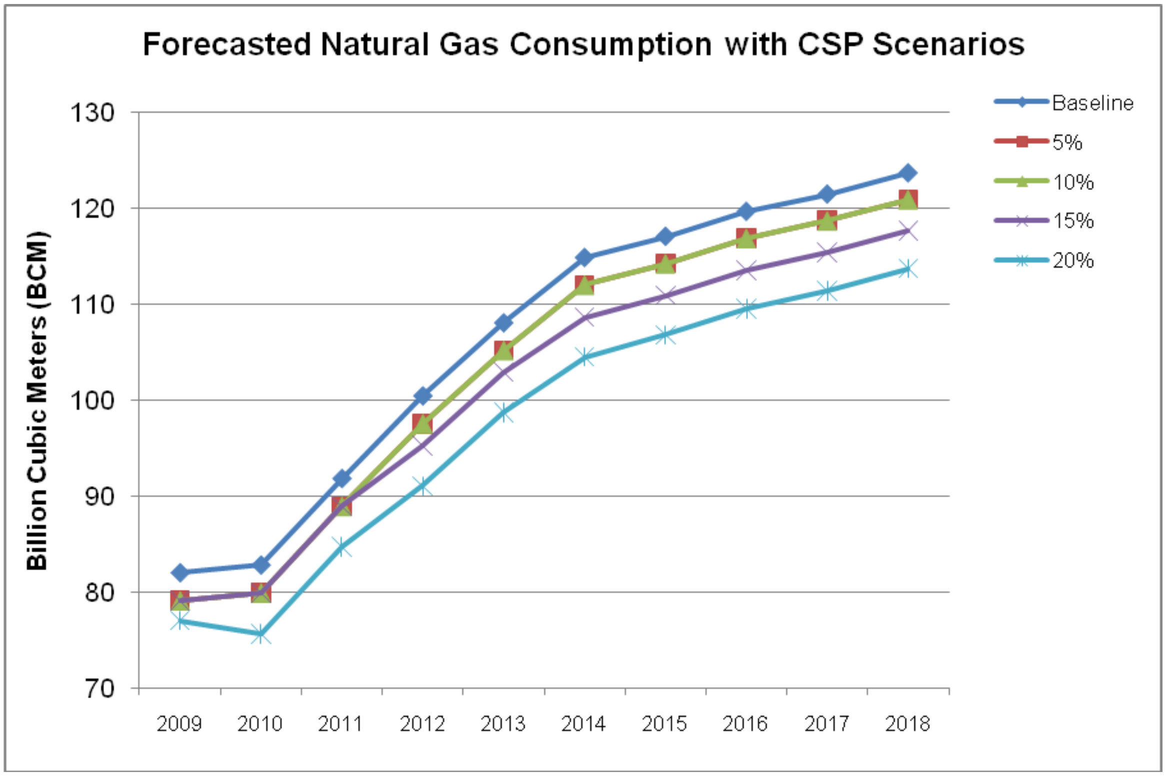


Figure 21: Forecasted Natural Gas Consumption with CSP Scenarios

In order to get a better idea of how much of the difference of the natural gas consumption per year in each scenario, the percentage difference against the baseline scenario was calculated. Figure 22 contains the percentage difference in forecasted natural gas consumption against the baseline scenario. The 5% and 10% scenario have the same percentage difference. The 20% scenario has a range of 6% to 9% reduction in forecasted natural gas consumption, depending on the year. The 15% and 5%/10% scenarios have the same percentage reduction until 2012, when the 15% scenario replaces more natural gas power plants than the other two scenarios.

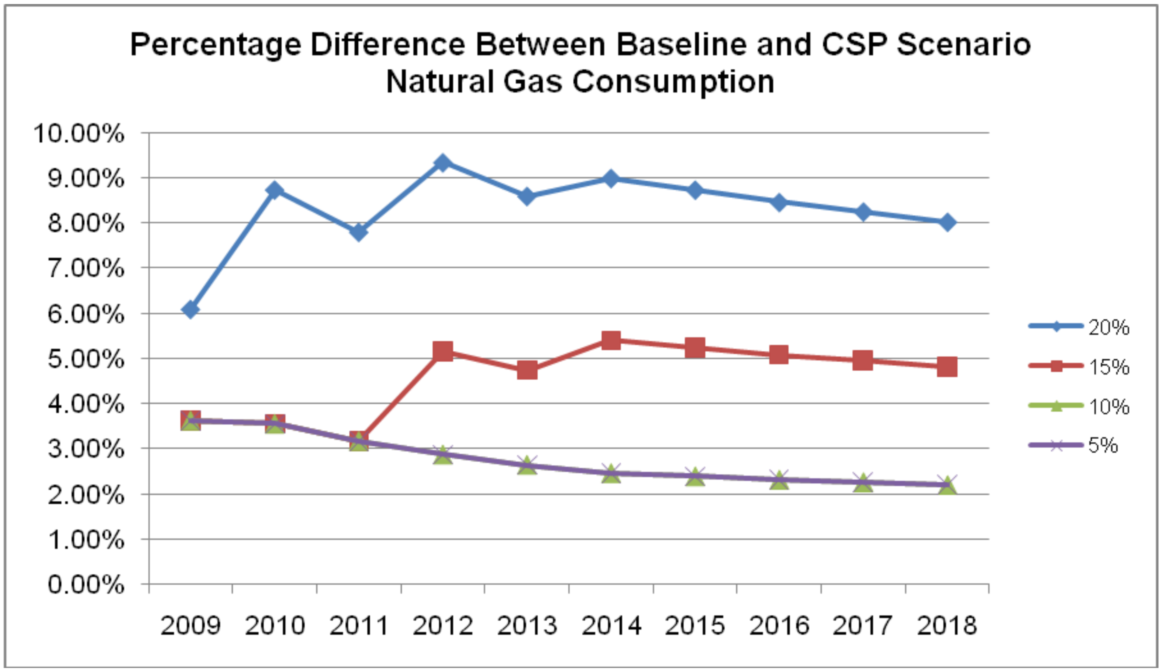


Figure 22: Percentage Difference Between Baseline and CSP Scenario Natural Gas Consumption

Overall, with CSP integration, there is a reduction in natural gas consumption but no scenario goes beyond a 9% reduction. The 15% scenario peaks at approximately 5.5% reduction but then goes down to 5% by 2018.

Chapter VII: Environmental Impact and Emissions

An Overview of Carbon Emissions in Saudi Arabia

A primary driver in pursuing renewable energy is to reduce green house gas emissions, a global climate change. Comparatively, Saudi Arabia is not ranked high in terms of cumulative green house gas emissions. According to the United Nations Data, Saudi Arabia is ranked as the 15th highest cumulative emitter of carbon dioxide in 2006 (United Nations, 2006). Countries that rank higher, from least to greatest, are France, South Africa, Mexico, Iran, Italy, Republic of Korea, Canada, United Kingdom, Germany, Japan, India, Russia, USA, and China. According to the Union of Concerned Scientists, Saudi Arabia is ranked 14th in 2006 (Union of Concerned Scientists, 2009). Figure 23 contains the top 20 countries in terms of carbon dioxide emissions sourced from the Union of Concerned Scientists (2009).

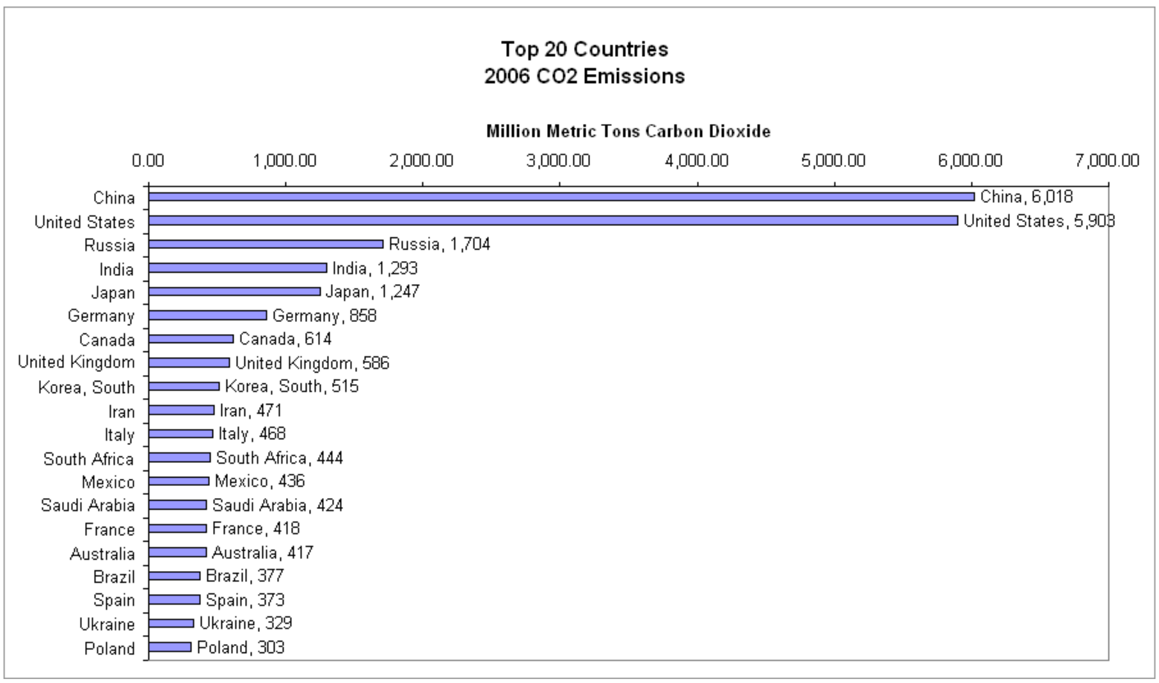


Figure 23: Top 20 Countries in CO2 Emissions (Union of Concerned Scientists, 2009)

Saudi Arabia is ranked 14th in terms of carbon dioxide emissions per capita in the year 2006 (United Nations, 2006), the country ranked the highest in this category is another GCC country, Qatar. In fact the rest of the GCC countries including, the United Arab Emirates, Kuwait, Bahrain and Oman are ranked higher than Saudi Arabia. This is most likely due to their intensive fossil fuel production and the countries' small national populations.

Currently, there is no strong push to reduce green house gas emissions in the Kingdom beyond the university research level. It should be noted that Saudi Arabia has formally given their support to the Kyoto Protocol (Arab News, 2004). Since Saudi Arabia is considered as a developing country, there is no obligation to cut emissions under the Kyoto Protocol. Due to the lack of obligation of emission cuts, Saudi Arabia has not taken any formal steps in reducing green house gas emissions. Should the Kingdom become more proactive in reducing emissions, this section would be useful in terms of expected carbon dioxide offset from solar integration.

Emission Reductions by Scenario

With the elimination and replacement of gas and steam (oil) power plants with concentrated solar power plants, a reduction in carbon dioxide and other green house gasses is expected. This section will go over the set up of calculating the emissions reduction by scenario.

There are several issues to consider when calculating carbon emissions including fuel source. Natural gas is considered one of the cleanest burning fossil fuels, in terms of carbon dioxide emissions. Emissions from fuel combustion are calculated by using a predetermined emission factor of the fuel. Emission factors are an estimated amount of emissions released from the combustion of a type of fuel. There is a high degree of certainty of carbon dioxide emissions due to the high certainty of carbon content of the fuel. According to the Intergovernmental Panel on Climate Change (IPCC) the emissions factor of dry natural gas is 56,100 kilograms of CO_2 per terajoules (kg/TJ) (IPCC, 1996). On the other end of the fossil fuel spectrum, lignite has an emission factor of 101,000 kg/TJ (IPCC, 2006). In between, crude oil has an emission factor of 73,300 kg/TJ (IPCC, 2006). In these calculations the emission factors of dry natural gas and crude oil will be used.

A baseline of carbon dioxide emissions from electricity generation will need to be calculated. Since the emission factors of dry natural gas and crude oil are different, there needs to be an understanding of how much electricity is generated from each fuel source as well as the amount of electricity generated. Figure 2 that has been shown previously, contains the forecasted electricity demand. Unfortunately, the forecast does not break down the electricity generation by fuel source. Another report that focuses on power generation in Saudi Arabia including a five year forecast contains a breakdown of fuel source of power generation (Business Monitor International Ltd., 2009). The percentage of power generation derived from natural gas fluctuates from 53% to 42% within the time period of 2007-2014. The forecast does not go beyond 2014, but this study goes beyond. In order to simplify the percentage of natural gas power generation, the average was taken which was 46.3% of power generation coming from natural gas. Using this percentage as well as the forecasted numbers depicted in Figure 5, the forecasted baseline of carbon dioxide emissions from electricity generation can be calculated. Figure 24 depicts the forecasted baseline scenario of carbon dioxide emissions from electricity generation. Even though almost half of the electricity is generated from natural gas, more carbon dioxide emissions are emitted from crude oil sources of power generation. This is due to the higher emission factor of crude oil, which was explained earlier in this section.

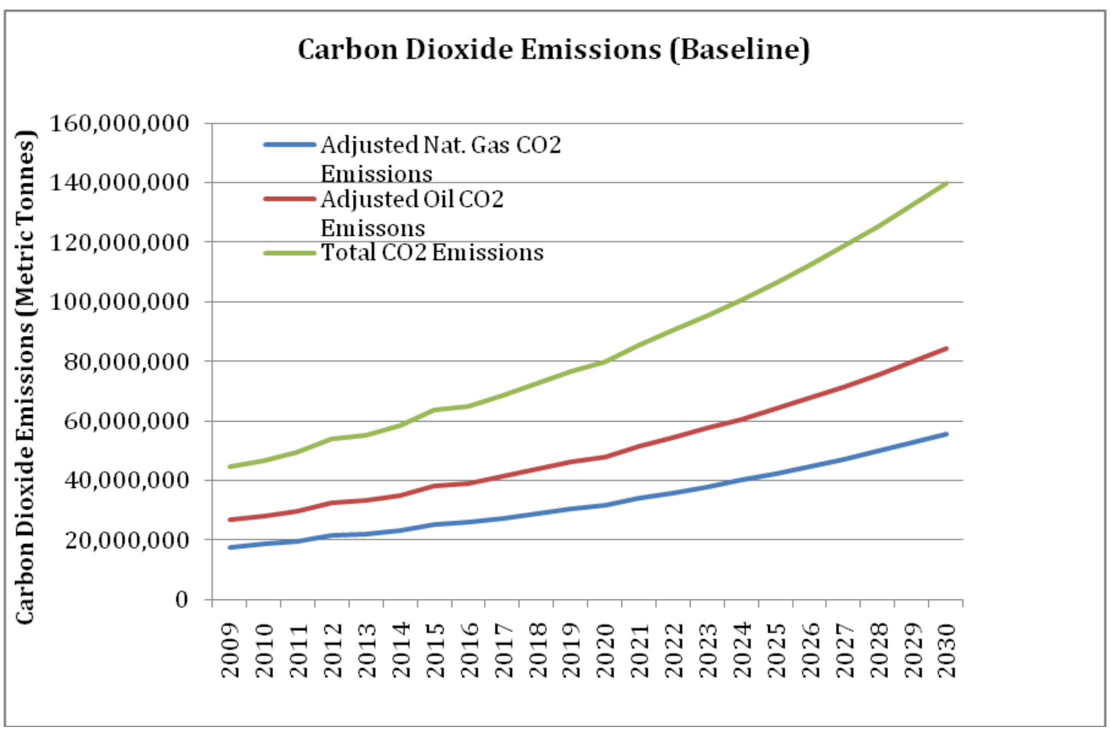


Figure 24: Carbon Dioxide Emissions (Baseline)

Carbon Dioxide Emissions of Each Scenario

In previous chapters in this report, the annual kilowatt hours generated was calculated. Using these previous numbers along with the natural gas and crude oil power plants offset by CSP plants, the forecasted carbon dioxide emissions were calculated for each scenario. It is assumed that electricity generated from CSP plants emit no carbon dioxide, this does not take into account the carbon dioxide emitted during the entire lifecycle of these plants. Figure 25 graphs the forecasted carbon dioxide emissions from all electricity generation of each scenario. As can be seen, as more CSP integration occurs, there is a progressive reduction in carbon dioxide emissions. The 15% and 20% scenarios have a level amount of annual carbon dioxide emissions from 2000 to 2016. This is due to the aggressive construction of CSP plants that have replaced many of the planned fossil fuel sourced power plants.

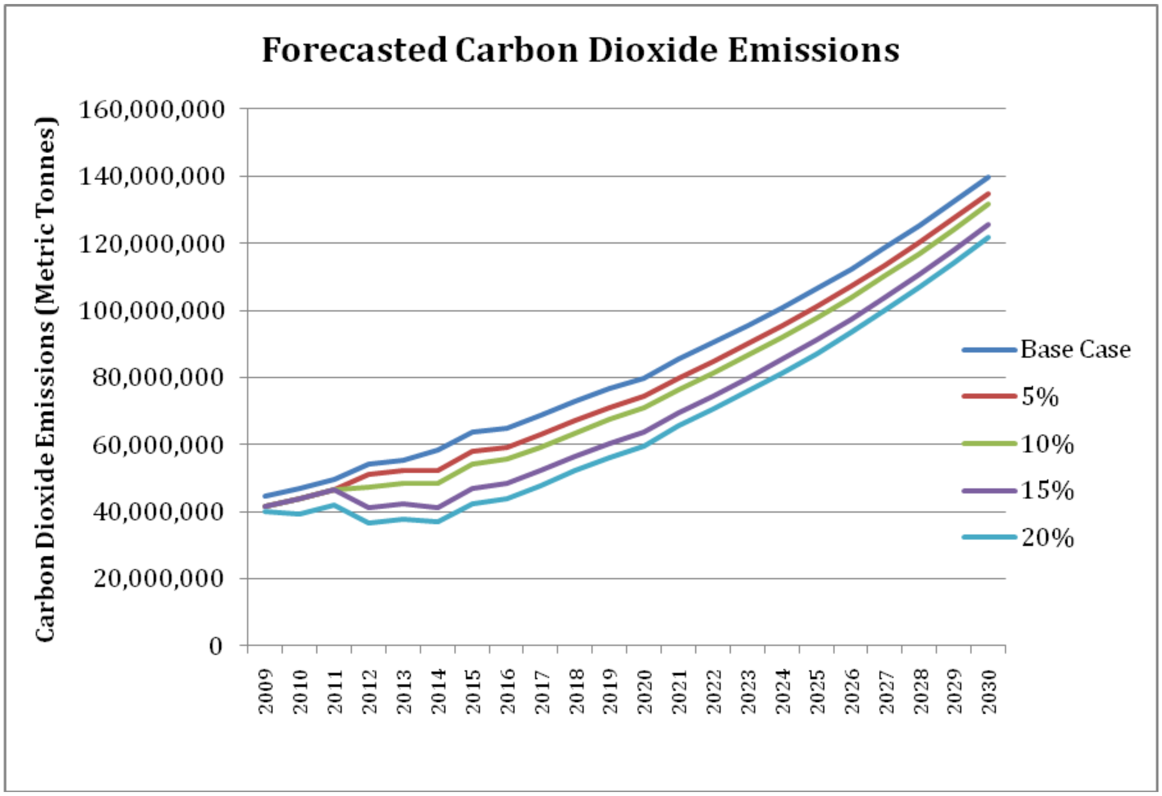


Figure 25: Forecasted carbon dioxide emissions from electricity generation.

Figure 26 takes the percentage difference between the forecasted annual carbon dioxide emissions and the forecasted annual carbon dioxide emission of each scenario. The greatest reduction in carbon dioxide emissions is in the year 2014 for all scenarios. The

20% scenario has over a 35% reduction in carbon dioxide emissions compared to the base case. This is due to the fact that many of the planned fossil fuel power plants were scheduled to be commissioned in 2014. Therefore, the expected emissions are greatly reduced, and the power generation is sourced from CSP. After the peak in 2014, the percentage begins to fall especially after 2020. This is due to the fact that CSP construction ends in 2020 in these scenarios. Therefore the assumed increase in power generation is sourced from newly constructed fossil fuel based power plants after the year 2020. This then dilutes the effectiveness of carbon dioxide offsets from CSP electricity generation. This graph highlights the non-linear relationship of the CSP construction plans in conjunction with expected electricity demand.

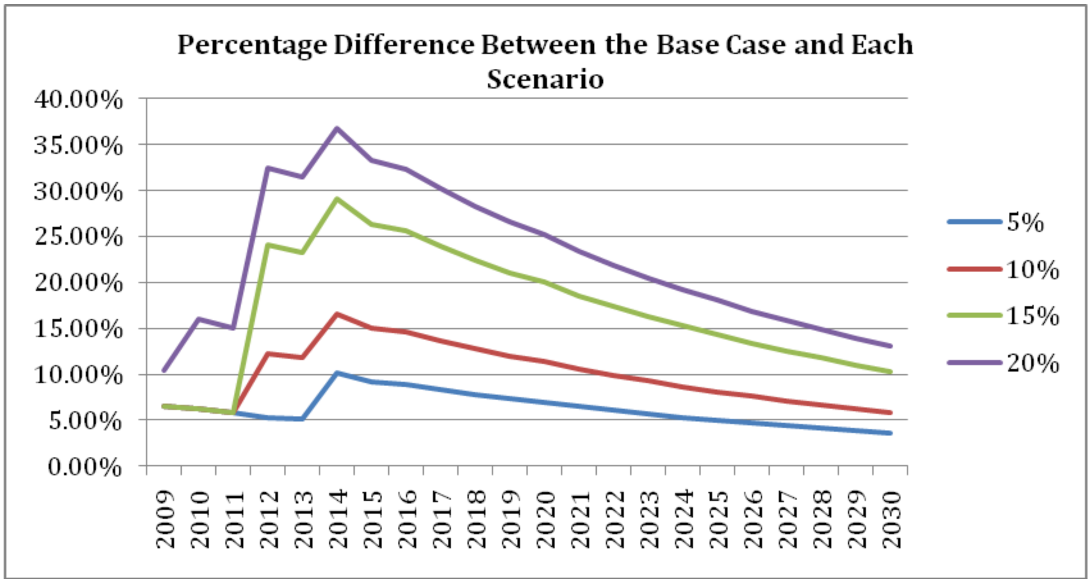


Figure 26: Percentage difference of forecasted annual carbon dioxide emissions between the base case and each scenario.

As mentioned before, it is expected to see a decrease in carbon dioxide emissions after integrating power plants that do not emit little to any carbon dioxide. More importantly, the issue is the degree of reduction of carbon dioxide emissions. Figure 27 has the total amount of carbon dioxide emissions avoided for each scenario between the years 2009 to 2030. The 5% scenario has an estimated 107,680,623 metric tonnes of carbon dioxide avoided from the base case. On the other side of the spectrum, the 20% scenario offsets an estimated 391,190,753 metric tonnes of carbon dioxide.

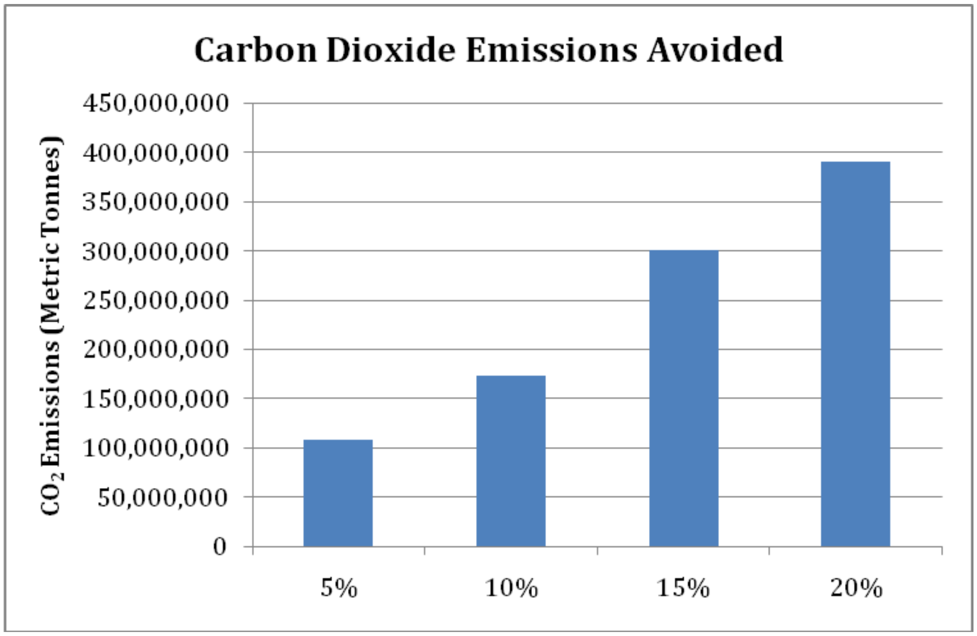


Figure 27: Carbon dioxide emissions avoided compared to the Base Case.

Another way to compare the differences in carbon dioxide emissions is by comparing each scenario by the scenario emission factor. The emission factor highlights the degree of carbon dioxide emission by weight per terajoules. As mentioned earlier, according to the IPCC, the emission factors of dry natural gas and crude oil are 53,100 kg of CO_2/TJ and 73,300 kg of CO_2/TJ, respectively. Figure 28 contains the calculated emission factors of each scenario between the years 2009-2030 as well as the emission factors of dry natural gas and crude oil. The following is the formula used to calculate the emission factor of each scenario between the years 2009 and 2030:

Emission Factor (kg of CO2/TJ)=(Total CO2 (kg))/((3,600 TWh/TJ)*(Total TWh))

The calculated emission factors of each scenario are shown in Figure 28. The blue bars represent the emission factors of each scenario and the red bars represent the emission factors of the two predetermined fossil fuels. From the stand point of the emission factor of crude oil, all of the scenarios have lower emission factors. Should all electricity generation in Saudi Arabia be derived from crude oil, the emission factor would equal that of the emission factor of the crude oil feedstock. Even though the base case has no CSP integration, the emission factor is still lower than that of the emission factor of crude oil. This is due to the natural gas fired power plants and the lower emission factor of the natural gas feedstock.

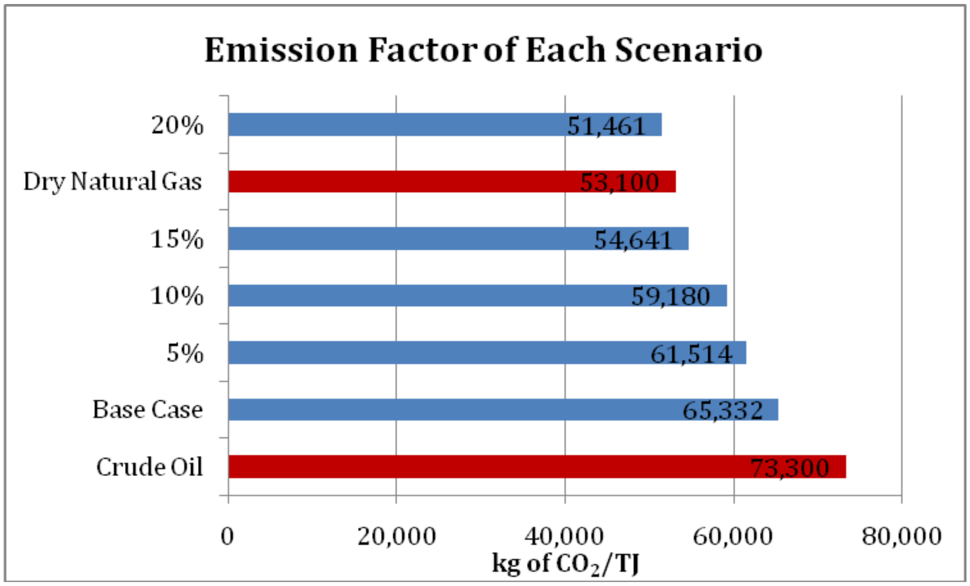


Figure 28: Emission factors of each scenario and feedstock of natural gas and crude oil.

Only the 20% scenario has a lower emission factor than that of the dry natural gas feedstock. The other scenarios fall between the emission factors of crude oil and dry natural gas. Therefore, should all of the crude oil power plants be converted to natural gas power plants, the carbon dioxide emitted would be less than all but the 20% scenarios that include all three types of power plants (CSP, crude oil, and natural gas).

This helps highlight that comparatively, CSP integration does reduce carbon dioxide emissions but are most effective when they are offsetting crude oil power plants. Even though 20% of the electricity capacity is from CSP, there is only a slight decrease in emission factor compared to the hypothetical all natural gas sourced electricity.

Life-Cycle Analysis

The previous section went over the carbon dioxide emissions of the actual power generation in each scenario. But these emissions accounted are from the generation and did not factor in carbon emissions from other areas such as construction, fuel transport and decommissioning. In this case, a life cycle analysis is needed to create a more complete picture on the environmental impacts of these scenarios.

Due to the complex nature and the need for accurate information, a life cycle analysis is beyond the scope of this study. There are too many unknowns to proceed with this analysis.

Discussion

Overall, there is a forecasted reduction in carbon dioxide emission as CSP integration is increased. As shown in Figure 27, the expected carbon dioxide emissions avoided in the 20% scenario is approximately 391,000,000 metric tonnes. To put this in perspective, in 2006, Saudi Arabia emitted a total of 381,564,000 metric tonnes of carbon dioxide, not just carbon dioxide emitted from electricity generation but also from transportation, industrial emissions and other sources of emissions (See Figure 29). The 20% scenario, over the span of approximately 20 years avoided the equivalent of all carbon dioxide emissions in the year 2006 in Saudi Arabia.

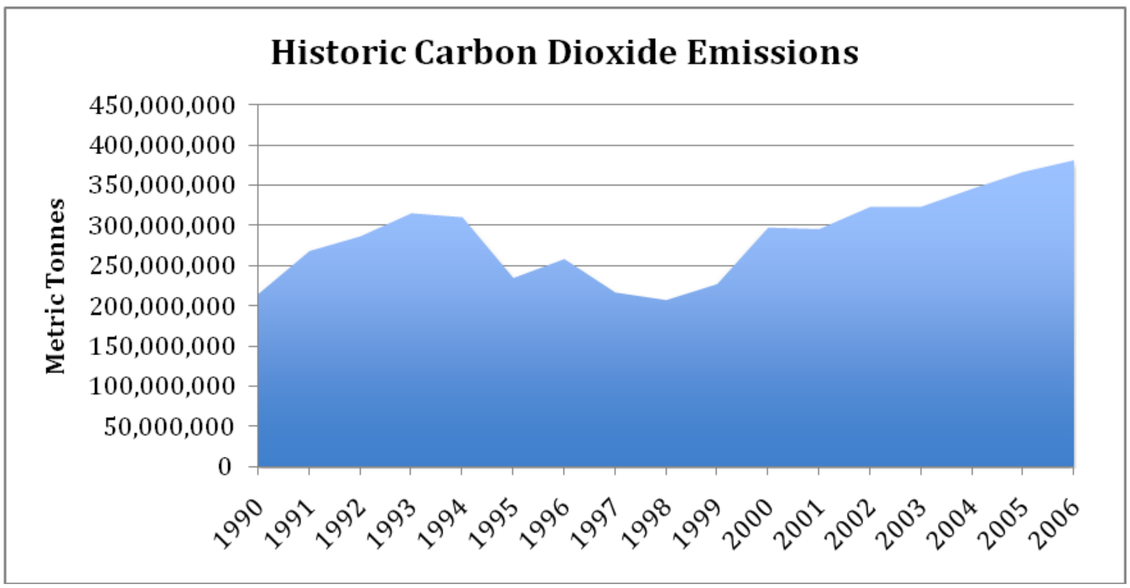


Figure 29: Historic carbon dioxide emissions from all sectors in Saudi Arabia (United Nations, 2006)

From a strictly carbon dioxide emissions reduction and avoidance, CSP integration, from a cost perspective, would be more costly than converting all crude oil power plants into natural gas power plants as well as building strictly natural gas power plants. This is quite evident in Figure 28. The emission factor of dry natural gas set at 53,100 kg of CO_2/TJ, while the emission factor of scenarios 15% and 20% are 54,641 kg of CO_2/TJ and 51,461 kg of CO_2/TJ, respectively. To this extent, from a cost point of view, pursuing a strictly natural gas powered would be the better option to pursue, with several major caveats. As mentioned before, Saudi Arabia is facing a production and supply bottleneck for natural gas. Due to this short supply, many of the power plants use crude oil as a feedstock, thus cannibalizing their number one export due to heavy subsidies for domestic consumption. The other issue that needs to be addressed is the concern with having one source for electricity generation. In this instance, using natural gas as the sole source for power generation could be a great liability. Even though there is no issue with importing natural gas and crude oil and problems with energy security facing many net importers of energy, subsidizing and promoting the excessive consumption of a fuel source could potentially lead to the unsustainable depletion of their natural gas resource. As mentioned earlier, Saudi Aramco is currently exploring for non-associated natural gas reserves with some success (Energy Information Administration, 2008). This is due to the growing demand for natural gas. With the issue of reducing the demand of natural gas as well as diversifying the energy mix, pursuing a strictly natural gas based electricity market would not be an ideal path the pursue. With regards to carbon dioxide reduction, pursuing a 20% or 15% scenario would have the have similar carbon dioxide offsets to that of an all natural gas power economy.

Chapter VIII: Scenario Selection

Overview of the study

This study is has a series of decisions and analysis that was taken into account in terms of properly evaluating the viability of solar integration into the Saudi Arabian electric mix. This study is primarily looking into solar integration to address several domestic as well as international concerns.

Saudi Arabia is currently in a natural gas production bottleneck. This is due to the growing demand for natural gas feedstock in both the industrial/petrochemical sectors as well as power generation. Saudi Arabia does have the fourth largest proven reserve of natural gas in the world, estimated at 258 trillion cubic feet (Energy Information Administration, 2008). Even though Saudi Arabia has the 4th largest reservoir of natural gas, 57% of the proven natural gas reserve consists of associated gas, 1/3 the total reserves are found in the onshore Ghawar field (Energy Information Administration, 2008). Therefore a majority of the producible natural gas is tied to crude oil production. The production schedule of Saudi's crude oil with the secondary production of natural gas does not meet the demand level for domestic natural gas consumption. Therefore, there is a push for non-associated natural gas exploration to better meet the country's growing demand. Many of the new power plants being built will be using crude oil as the primary feedstock due to the fact that natural gas production does not fully meet demand. This then creates a dilemma of cannibalizing the country's major export of crude oil, since much of the domestic crude oil prices are highly subsidized.

Using solar electricity power generation could potentially alleviate some of the natural gas demand, thus reducing the need for immediate natural gas exploration as well as reducing the need for new crude oil based power plants. Thus the crude oil used for domestic consumption at subsidized costs can be sold in the international open market at a much higher price point.

Currently, almost all of Saudi Arabia's power mix consists of natural gas single and combined cycle power plants and crude oil thermal power plants. Diversifying the power portfolio could reduce certain risks such as natural gas shortages as well as crude oil cannibalization. With Saudi Arabia's incredible growing demand for energy, diversifying the sources of electricity generation would be a welcome addition.

From an international point of view, Saudi Arabia is one of the top 15 countries in carbon dioxide emissions, from both a cumulative and per capita basis. Even though Saudi Arabia is not obligated to curb green house emissions being a signatory of the Kyoto Protocol, proactively reducing emissions would be a benefit to the international community. Being a leader in crude oil production, Saudi Arabia may gain some positive public relations within the international community in terms of environmental issues. The United Arab Emirates has taken a proactive approach in diversifying their economy. Instead of being a prominent leader in solely fossil fuel energy, the U.A.E. is attempting to become a world leader in energy, with a focus on alternative and renewable energy.

With a vast national endowment and ideal solar resource, Saudi Arabia is in a position to capitalize on becoming a prominent leader in utility scale solar energy.

Solar Technology Selection

The parabolic trough concentrated solar power technology is the ideal choice for solar integration in Saudi Arabia. Due to the country's high direct irradiance and number of cloudless days, concentrated thermal power would capitalize this abundant resource. Of the three major CSP technologies which include parabolic trough, dish system, and power tower, the former technology is the most mature of the three. Therefore there are many suppliers and manufacturers specializing in parabolic trough. Investing in a proven and commercial scale technology reduces construction and supplier risks.

There are several key points why CSP was selected over photovoltaic technologies. PV technology does not have a commercially viable backup system. Therefore the dispatchability of PV generated electricity is a major drawback. CSP plants have the option of thermal storage which means after the sun sets, power can still be generated using the stored heat to generate electricity for several hours. Thermal storage has the ability to act as a buffer system. Should there be cloud cover, the decrease in solar irradiance can be counteracted with the stored heat and the electric generation would not dramatically decline. A final reason why CSP would be the ideal technology is due to the similar layout and power generation scheme as traditional power plants. The learning curve in building, planning and the operation & maintenance may not be as steep as integrating utility scale PV power plants.

Cost Modeling and Scenario Outcomes

A total of four scenarios were used to assess the degree of solar integration. In this case the five scenarios include base case (0% CSP integration), 5% CSP integration, 10% CSP integration, 15% CSP integration, and 20% CSP integration. As mentioned before, a study has assessed that with current transmission technologies, the upper limit of intermittent power generation is limited to a maximum integration of 15 to 30% (Grubb & Meyers, 1993). Therefore in this study, a conservative upper limit was chosen to be at 20% integration.

The first sets of models were set so that the price of electricity remains constant throughout all of the scenarios. The net present values of each power plant, both planned conventional power plants and CSP power plants were calculated using the National Renewable Energy Laboratory's modeling program, Solar Advisor Model (SAM). Only the NPV of the newly constructed power plants between the years 2009 to 2020 were calculated.

An alternative scenario was proposed in which the cost average cost of electricity would be increased by assuming the real true cost of all electricity generated from conventional sources is pegged at $0.03/kWh. The cost of the electricity generated by each type of CSP plants were derived from the calculated real levelized cost of energy. This was then used to create a new cost of electricity which the NPV of each scenario was calculated. It is assumed that the cost of electricity generated will be the price of the electricity sold. All of these figures are compiled in Figure 30. With a slight increase in the average electricity price, the 15% scenario has a similar NPV to that of the base case scenario with no price increase.

With regards to the issue of project value, all of the NPV's have negative value. Therefore, from a standpoint of not increasing the cost of electricity, the base case would be the proper scenario to pursue. But should there be a push to integrate CSP generation into the electricity mix; the 15% scenario would be the ideal scenario due to the similar NPV's of that of the base scenario. The price increase to the consumer would need to be further assessed in terms of personal economic impact.

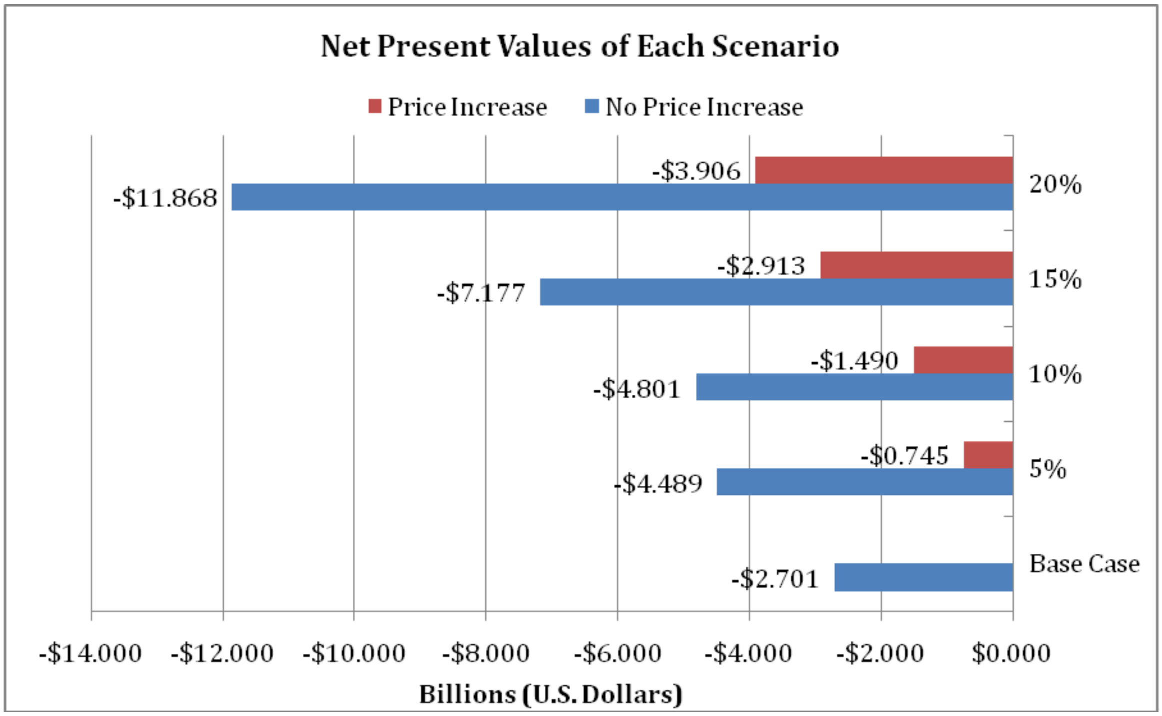


Figure 30: Comparison of no price increase vs. price increase of each scenario.

Natural Gas Reduction Outcomes

As stated previously, natural gas supply is currently in production constraints. It is assumed that integrating CSP into the electricity mix will help reduce the demand for natural gas. The issue at hand is what degree CSP integration will have on natural gas demand as well as crude oil consumption avoidance which then can be exported. The primary driver in this section is to reduce natural gas consumption. A secondary driver would be a reduction in crude oil consumption, more due to issues of cannibalizing their export rather than production issues. After calculating expected reduction in natural gas consumption in each scenario, there is a clearer picture of the impact CSP integration has on natural gas demand. Figure 31 best captures the effect CSP integration has on the natural consumption. With the 20% scenario, there is a reduction in consumption at approximately 8% throughout the timeline. The 15% scenario has a reduction at around 4-5% from the baseline. These numbers show that a significant portion of natural gas consumption is used elsewhere, mainly in the industrial and petrochemical sectors. Without considerations such as total cost, the 20% scenario would be the best option to pursue if the only goal with CSP integration was the reduce natural gas consumption.

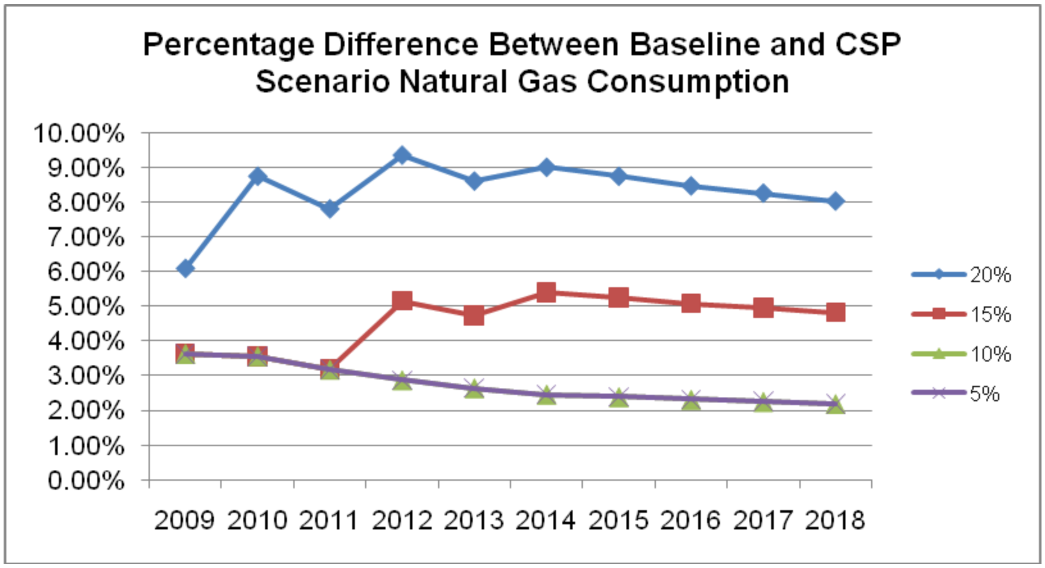


Figure 31: Percentage difference in natural gas consumption between baseline and CSP scenarios.

Carbon Dioxide Reduction Overview

It is expected that with the integration of CSP there will be a reduction in green house gas emissions due to the number of conventional power plants being offset. Similar to the issue with natural gas reduction in consumption, the primary issue is how much an impact CSP integration has on overall green house gases emissions. In this case, carbon dioxide will be used as a proxy for all green house gas emissions. As can be seen in Figure 32, the cumulative reduction within the timeline of 2009 to 2030, the 20% scenario would offset just less than 400,000,000 metric tonnes of carbon dioxide. With the other issues not given any weight, the 20% scenario would be the best option to pursue should the single concern was to reduce green house emissions.

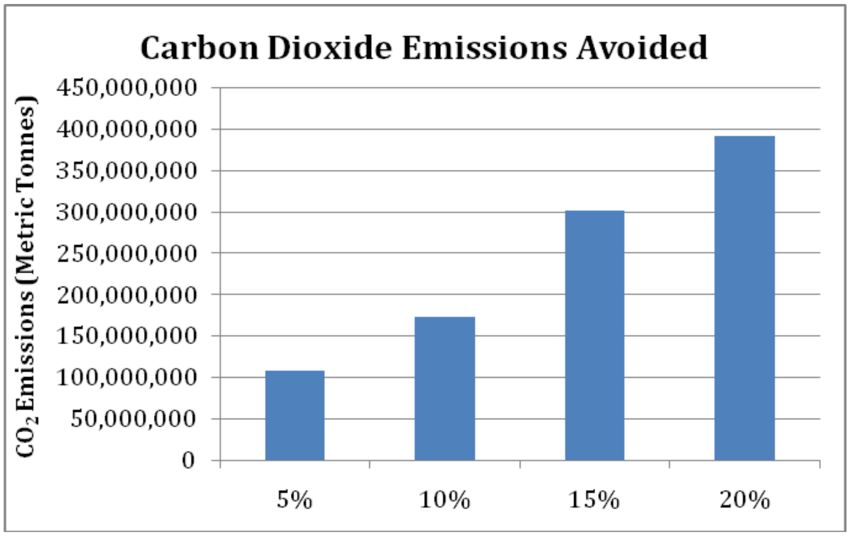


Figure 32: Carbon dioxide emissions avoided compared to the Base Case

Overall Scenario Selection

With several criteria to consider, picking the appropriate scenario is dependent on the weight of each of the major criteria. Overall there are three major criteria that have been assessed:

- Scenario cost in the form of net present value
- Fossil fuel consumption reduction, with greater emphasis on natural gas
- Carbon dioxide reduction of each scenario

Another criterion that has not been measured is the degree in energy diversification. Within this study, there has not been a firm definition and constraints in terms of quantifying the ideal energy diversification. This study simply states that diversifying the electric portfolio beyond just natural gas and crude oil is a form of insurance or a hedge against the uncertainty of natural gas reserves and production as well as the depletion of a fixed resource.

With these three criteria, it is up to the decision maker to place weights on these three. There are more criteria that should be assessed and analyzed but they are beyond the scope of this study. Additional criteria that should be assessed will be discussed later.

Since it is up to the government of Saudi Arabia to select a scenario, the primary focus would be the overall benefit of the country's citizen and the overall health of the kingdom from both a short term and long term point of view.

Cost would most likely be the primary concern with integrating CSP in the country's energy mix. This study suggests four overarching viewpoints (options) Saudi Arabia should consider. The four are the following:

1. Select the cheapest option.
2. Select the cheapest solar option without having to raise electricity prices.
3. Select a solar option that would create a larger amount of solar integration without detrimental effect on the financial integrity of the government and its citizens.
4. Select the option that maximizes natural gas offsets with the secondary concern with cost.

In order to assess these alternatives, the analytic hierarchy process will be used. This process uses both quantitative and qualitative assessments that are broken down into a hierarchy of sub-problems. Each level of criteria has weight system. This process will help evaluate each criterion with each possible alternative (Base Case, 5%, 10%, 15%, 20%) that best fits each option.

The weight system for fossil fuel consumption and carbon dioxide offsets uses a quantitative approach. The criterion for fossil fuel will be broken down into two sub-criteria, natural gas offset and crude oil offset. The quantitative weighting system will focus on the cumulative avoided consumption of these two fuel sources, which can be referred to in Figure 18. The baseline scenario has 0's since the scenario does not offset fuel consumption. The other scenarios are basing the offsets based on the baseline. Therefore, there is no weight assigned to the baseline scenario. The weighting calculation of avoided carbon dioxide emissions is the same as the fossil fuel offset. The 0 in the baseline scenario means that the other scenarios are basing the offsets to the baseline.

Table 15: Fossil fuel/carbon dioxide weights adjusted for avoided consumption/emissions

	Natural Gas (BCM)	Weight	Crude Oil (bbl)	Weight	Tonnes of CO2	Weight
Baseline	0	0	0	0	0	0
0.05	66	0.125	0.476	0.092391	1.08E+08	0.110569
0.1	66	0.125	1.146	0.222438	1.73E+08	0.178154
0.15	146	0.276515	1.765	0.342585	3.02E+08	0.309594
0.2	250	0.473485	1.765	0.342585	3.91E+08	0.401683

With the issue of cost, a more qualitative approach was used to assign a weight for each scenario. An analytical hierarchy process program was used to assess the qualitative approach to assigning weights (Canadian Conservation Institute, 2005). The reasoning behind this is that the NPVs of the price increase compares the NPVs of the price increase NPVs of each scenario that has solar integration (5%, 10%, 15%, and 20%) against the NPV of the base case with no price increase. This is due to the fact that the reason for the price hike is to recoup some of the cost of solar integration without the country having to pay from government money. Therefore, the NPV of the base case with the price increase was not calculated since there is no solar integration to warrant a price increase. The second and third options exclude the base case as a scenario since these two options call for some sort of solar integration.

The following figure illustrates the hierarchy of the of this decision analysis:

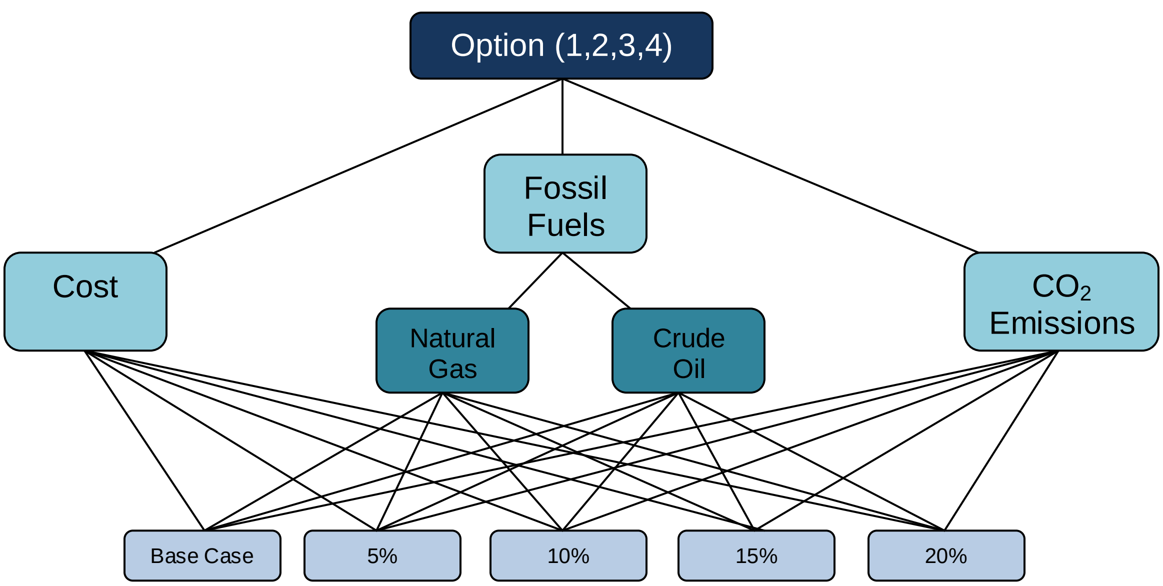


Figure 33: Decision Hierarchy

Option 1: Scenario Selection

As mentioned earlier, Option 1 focuses mainly on the cheapest option with some concern with natural gas offsets. In this case, the cheapest option would be the scenario that would not affect the electricity prices the citizens would have to pay. There is some concern with natural gas consumption but little to no concern to green house gasses.

The following weights were calculated by comparing the importance of each criterion with each other.

- Total Cost (Cost): 0.726
- Fossil Fuel Reduction (Crude Oil and Natural Gas): 0.208
  - Crude oil was given a 0.3 weight (0.0624)
  - Natural gas was given a 0.7 weight (0.1456)
- Green House Gases Emissions (GHG's): .065

The following table contains the sum of the calculated weights of each scenario (alternative) and the corresponding criterion. Each calculated weights are then added together by their scenario. The scenario with the highest number is the best choice with respect to all of the quantitative and qualitative weights of the criterion.

Table 16: Results of Decision Hierarchy of Option 1

	Weight	Base Case	5%	10%	15%	20%
Cost	*0.726*	0.2273	0.1855	0.17817	0.1226	0.01279
Natural Gas	*0.0624*	0	0.0182	0.01824	0.0403	0.06907
Crude Oil	*0.1456*	0	0.0058	0.01391	0.0214	0.02142
GHG's	*0.065*	0	0.0072	0.01163	0.0202	0.02623
Sum Total		**0.2273**	**0.2167**	**0.22194**	**0.2045**	**0.12951**

Due to the heavy emphasis towards cost and some importance with natural gas, the ideal choice would be the base case, which barely edged over the 10% scenario. Should there be a greater emphasis on fossil fuel conservation, it is likely that that the 10% scenario would be the ideal choice to pursue. Even though all but the cost criterion was calculated as a 0 in the base case, the greater emphasis on cost overcame the benefits of conservation and emissions that were calculated in the other scenarios.

Option 2: Scenario Selection

In this case, Option 2 emphasizes on selecting the cheapest solar option. Therefore the base case does not apply since it does not integrate CSP. The weights of each criterion were not altered since there is a greater emphasis on price with a secondary importance on natural gas conservation, similar to that of Option 1.

The table below contains the calculated weights of each scenario with each criterion. After calculating the sum total, the ideal choice would be the 10% scenario. From a strictly cost point of view, the 5% scenario would have been the best choice but there was some importance on fossil fuel conservation as well as green house gas emissions in this decision analysis. It also should be noted that there is the difference between the NPVs of the 5% scenario and the 10% scenario is approximately 6%. Therefore a slight increase in NPV with greater fossil fuel offset and emissions outweighs the 5% scenario advantage of a slightly lower NPV.

Table 17: Results of Decision Hierarchy of Option 2

	Weight	Base Case	5%	10%	15%	20%
Cost	*.726*	0	0.234796	0.225338	0.135077	0.131037
Natural Gas	*.208*	0	0.018235	0.018235	0.040338	0.069072
Crude Oil	*.208*	0	0.005776	0.013907	0.021418	0.021418
GHG's	*.065*	0	0.00722	0.011633	0.020216	0.02623
Sum Total		**0**	**0.266027**	**0.269113**	**0.21705**	**0.247757**

Option 3: Scenario Selection

Option 3 focuses on solely solar integration, therefore eliminating the base case. This time there is still a focus on cost but less so compared to the other two scenarios. This is due to the slight increase importance on fossil fuel conservation as well as very slight increase in importance on green house gases. It should be noted that the cost section was calculated qualitatively. The electricity price increase was used to reduce the financial burden on the government. The price increase helped offset the capital costs of CSP plants, thus reducing the negative NPV's. That section also emphasized on how close each NPV of each scenario was to the NPV of the base case scenario. In this case the 15% scenario had similar NPV's to that of the base case. The qualitative calculation takes the importance of how close the solar scenarios are to the base case NPV. The table below contains the qualitative weight calculations. With an emphasis on the having an NPV similar to that of the base case, the 15% scenario has the greatest rating at 0.3776. Notice that the 20% scenario has the lowest rating within the solar scenarios at 0.0472. This is due to the NPV being significantly greater than the NPV of the base case.

Table 18: Qualitative Result of Weights of NPV's

	NPV (Billion $)	Weight
Base Case	-2.701	0
0.05	-0.754	0.2699
0.1	-1.49	0.3053
0.15	-2.913	0.3776
0.2	-3.906	0.0472

The following weights were calculated by comparing the importance of each criterion with each other according to the Option 3 statement.

- Total Cost (Cost): 0.571
- Fossil Fuel Reduction (Crude Oil and Natural Gas): 0.286
  - Crude oil was given a 0.3 weight (0.0858)
  - Natural gas was given a 0.7 weight (0.2002)
- Green House Gases Emissions (GHG's): 0.143

The following table contains the sum of the calculated weights of each scenario (alternative) and the corresponding criterion. Each calculated weights are then added together by their scenario.

Table 19: Results of Decision Hierarchy of Option 3

	Weight	Base Case	5%	10%	15%	20%
Cost	*0.571*	0	0.154221	0.174448	0.215761	0.026970
Natural Gas	*0.2002*	0	0.024999	0.024999	0.055300	0.094692
Crude Oil	*0.0858*	0	0.007919	0.019065	0.029363	0.029363
GHG's	*0.143*	0	0.015800	0.025458	0.044241	0.057401
Sum Total		**0**	**0.202939**	**0.24397**	**0.344665**	**0.208426**

After the calculations have been summed together, the scenario with the greatest total is the 15%. The reason for this is due to the greater importance of the NPV being closest to the NPV of the base case. It is interesting to note that the 5% scenario is ranked the lowest under the 20% scenario. The likely reason for this is the increased importance on fossil fuel conservation and natural gas conservation, which the 20% scenario has a heavy advantage over the 5% scenario. Therefore, for Option 3, the ideal selection would be the 15% scenario.

Option 4: Scenario Selection

Option 4 in this case, puts natural gas conservation as the most important with secondary importance on cost. There is also a greater importance to carbon dioxide emissions offset compared to the other scenarios, which is reflected in the weight of the criterion. In this Option, the base case is included since there is not a strictly solar constraint. The no price increase NPV set was also used. The following weights were calculated by comparing the importance of each criterion with each other according to the Option 4 statement.

- Total Cost (Cost): 0.328
- Fossil Fuel Reduction (Crude Oil and Natural Gas): 0.411
  - Crude oil was given a 0.3 weight (0.1233)
  - Natural gas was given a 0.7 weight (0.2877)
- Green House Gases Emissions (GHG's): 0.261

The following table contains the sum of the calculated weights of each scenario (alternative) and the corresponding criterion. Each calculated weights are then added together by their scenario.

Table 20: Results of Decision Hierarchy of Option 4

	Weight	Base Case	5%	10%	15%	20%
Cost	*0.328*	0.102592	0.083708	0.080412	0.055317	0.005771
Natural Gas	*0.2877*	0	0.035971	0.035971	0.079573	0.136255
Crude Oil	*0.1233*	0	0.011395	0.027433	0.042251	0.042251
GHG's	*0.261*	0	0.02887	0.046516	0.080835	0.10488
Sum Total		**0.102592**	**0.159943**	**0.190333**	**0.257976**	**0.289156**

After the calculations have been summed together, the scenario with the greatest total is the 20%. Even though the 20% scenario had the lowest cost calculation, especially compared with the base case (0.103 vs. 0.006), the greater importance on fossil fuel conservation and green house gas emission offsets overcame the cost criterion for this option. In this case, the base case has the lowest calculations since there is no offsets in fossil fuel and green house gas emissions.

Scenario Conclusions

These options were created to overview the variability of the decision analysis process. Depending on the criteria hierarchy as well as the degree of importance of the three criteria, the scenario selection will change. With the greatest importance on cost and minimal importance on the other two scenarios, the base case is selected.

With the case for Option 2 and the greatest importance on cost, the 5% scenario would have been the expected selection. But since there is still some importance on natural gas conservation and the NPV's being similar, the 10% scenario was calculated to be the ideal choice.

Option 3 integrated the price increase to match the NPV of the base case scenario. In this case, the NPV section was calculated in a qualitative manner to emphasize on the importance of being close to the base case scenario but not go over. In this case the 15% scenario was the overwhelming winner in this option.

Option 4 was created to highlight the greater importance of fossil fuel conservation as well as an increased, but still not as important as cost, importance of green house gas emissions offset. With this shift in importance, the 20% scenario had the creates total even though the scenario's cost calculation was very low.

The primary objective of this report is not to recommend a certain scenario, but to assess the viability of utility scale solar integration into a country that is fossil fuel abundant. With the information provided, solar integration is feasible, as long as the study's assumptions hold true in the real world. Therefore, it is up to the decision maker, in this case the Saudi government, to weigh in the pros and cons of solar integration and carefully assess the importance of each of the study's criteria provided. If there is a greater value on natural gas offsets, then there would be a greater importance on this criterion. If cost is an overwhelming importance over other criteria, then it is likely that the decision makers will opt not to pursue solar integration. In the end, this study provides some insight in the feasibility of solar integration. But it is up to the decision maker to choose what he/she wants to do with this information.

Chapter IX: Conclusion

This study's main focus is to provide insight into the viability of integrating solar energy into the Saudi Arabian electric mix. As mentioned before, there are many reasons why Saudi Arabia should integrate solar. These drivers include the reduction in natural gas consumption which could relieve some pressure on natural gas production. Solar integration could also reduce the expected crude oil consumption since close to half of the electricity generated is sourced from crude oil that has been subsidized by the government. Solar integration could mean that more crude oil can be exported than that of the base case scenario, thus providing a monetary added value. Solar integration would diversify the electricity mix which could reduce liabilities such as interruption in feedstock production or transport. Even though Saudi Arabia is not obligated to reduce green house gas emissions as stated in the Kyoto Protocol, there is a societal benefit in the reduction of these emissions via addressing the issue of global climate change.

On the other hand, there several drawbacks when it comes to solar integration. From a cost basis, solar integration cannot compete with Saudi Arabia's conventional power generation. The construction costs are lower than that of CSP plants. Most importantly, the crude oil and natural gas feedstock are highly subsidized, thus the cost of generation is exceptionally cheap. There will most likely be issues with transmission and siting. A large issue that has not been addressed in this study is the issue of operation and maintenance. Saudi Arabia has an ideal solar resource, but the drawback is the issue of the surrounding environment. The Saudi's landscape is made up of mostly desert; therefore there will be an issue of dust as well as moving sand dunes that could decrease the efficiency of these plants. Therefore, there is likely going to be a significant increase in O&M cost to maintain the plant's optimal efficiency. There is also the issue with CSP still in its commercial infancy. The technology is scalable but there are unknown risks with a technology that is not well established as compared to conventional power plants such as coal and natural gas-fired power plants.

Should there be a push for solar integration, many policy mechanisms will need to be established to help catalyze the planning and construction of these solar power plants. A large barrier to solar power plants is the initial capital cost. As mentioned in the

Chapter III, Saudi Arabia has a limited budget in the expansion of power generation. This is why recently there has been a move to 3rd party ownership of several new power plants due to governmental capital constraints. In this study, it is assumed that all of the CSP plants are utility owned with a majority of construction being financed. There are several other forms of business models that can be used to aid in the integration of CSP. According to the Solar Electric Power Association, there are three types of utility business models which include solar ownership, solar financing, and solar purchases (Solar Electric Power Association, 2010).

There are many mechanisms that could spur solar integration beyond owning the system. Many countries in Europe use feed-in tariffs to promote the proliferation of renewable energy development. Feed-in tariffs offer a long-term fixed price payment to the power plant owner from the utility entity. Typically, should the project fit all predetermined criteria, the project has guaranteed grid access and the utility is obligated to purchase the electricity at a predetermined rate. A power purchasing agreement is similar in which there is an agreed long-term purchasing agreement, but typically a PPA has an escalation rate during the contract. PPA's typically occur when a request for proposal (RFP) has been published for a power plant. In this case there is more competition to win the RFP and a feed-in tariff there has less competition to win lock in a contract. In this case, a feed-in tariff would have a set capacity cap and a PPA is more of a case-by-case scenario. Both of these mechanisms are considered as solar purchases.

Since there is a lack of experience with solar integration in Saudi Arabia, it may be advantageous for the government to transfer the liability to a 3rd party entity. Therefore the risk of financing, planning, construction and O&M would not lay upon the utility. The utility is only responsible for making payments for the electricity produced. Many PPA's have a purchasing option, in which the utility has the option to purchase the power plant after the PPA has expired. This may give the utility time to gain experience with the many aspects of building, owning and operating a CSP plant. In the long run, it is likely that utility ownership would be less costly than pursing a 3rd party ownership model. In the short run, 3rd party ownership would be advantageous for the utility to reduce risk and liabilities. Letting an experienced development company handle the lifecycle of the power plant would be a recommended course to pursue. Once the utility is able to manage the risks better through experience, utility ownership would eventually be the ideal avenue to pursue. Further study into creating a solar policy road map is needed to gain further insight.

Saudi Arabia is a booming economy due to the country's massive fossil fuel resource. There has been a proactive push to diversifying the economy so that the country would not simply rely on fossil fuel exports to further promote economic growth. An untapped resource Saudi has, in which most other countries do not have, is the solar resource. With much of the land unused and fast solar resource, there is a large potential for utility scale solar development. From a technical standpoint, solar integration is feasible in the Kingdom. In terms of financing, solar integration is possible due to the countries large financial reserve. The issue is whether there are cheaper options available. Conventional power plants currently are the cheaper option, but this is due to the high subsidies of the feedstock. There needs to be a thorough economic cost/benefit analysis of pursuing solar integration, especially with regards to offsetting natural gas and crude oil consumption.

The true cost of energy and electricity will need to be unraveled in order to provide a better analysis of the financial pros and cons of solar integration. There are direct electric subsidies as well as indirect subsidies such as feedstock subsidies. Currently the average price of electricity in Saudi Arabia is $0.03/kWh. In reality, this is the average cost of subsidized electricity. What is the actual cost?

There are many questions that still need to be answered in order for solar integration to be successful in a fossil fuel rich country like Saudi Arabia. This study has helped shine a light on many unknowns and has attempted to give a broad analysis of the feasibility of solar integration. This study is not meant to be a detailed proposal for solar integration for the Kingdom of Saudi Arabia. It is meant to create dialogue of the possibility of solar integration. It is meant to be a jumping off point.

Chapter X: Further Studies

This study covered several important aspects in the feasibility of solar integration in Saudi Arabia, but there are still several important issues that were not covered in this study that would be valuable in the decision making process. This study overviewed the technology selection, cost evaluation, natural gas and fossil fuel offsets and green house gas offset. This section will go over recommended further research.

With these scenarios, especially the aggressive 15% and 20% scenarios, there will be significant impact in the construction, service and finance companies. Therefore, it is recommended to research the potential job creation with the integration of solar. It is likely that domestic jobs will be created but there needs to be a thorough study in the extent of job creation. In other words, how many jobs will be created and in what sectors are these jobs going to be created when there is a significant demand for solar integration. With a new market, solar integration could provide Saudi Arabia with economic growth and gains in GDP. Once the CSP integration becomes mature, there may be a push for domestic manufacturing. Saudi universities may need to create and expand programs that focus on the engineering, planning, research and development and O&M of solar power.

There will need to be a study on the current electric transmission infrastructure and what needs to be improved in order to facilitate CSP plants. Unlike conventional power plants, CSP does not have the same degree in dispatchability. With thermal storage, CSP has the potential to buffer decreases in electricity generation during cloudy times of the day as well as generate electricity when the sun goes down to an extent. But this technology is still relatively intermittent. Therefore, this could provide a strain on the transmission infrastructure as it currently stands. The study would have to look into the desirable technological improvements as well as the management of these generation systems.

A careful study of the effect CSP generation has on the electric load at a daily, monthly, seasonal and yearly level will need to be conducted. This will then allow a better management of the balancing of load with regards to anticipating generation declines from CSP plants and counteracting this with increase power generation from conventional power plants. Integrating a large portion of an intermittent power source into the grid will need to be addressed in a careful manner and current protocols will need to be reassessed.

The issue with operation and maintenance in a desert environment would need to be addressed and studied. It is likely that O&M cost will increase in a desert environment. Therefore there needs to be some research with this issue. Only to a certain extent can modeling be useful, eventually there will need to be a pilot project in similar conditions to that of Saudi Arabia. Real world experience at a pilot scale will provide valuable insight with the potential challenges that will need to be addressed once the CSP integration is scaled up.

Another issue that Saudi Arabia is currently facing is water production. A majority of the water is sourced from the sea via water desalinization. This is a very energy intensive process. A study that looks into solar integration into water desalinization could be a potential scenario to pursue. A majority of water desalinization plants run off of crude oil (Energy Information Administration, 2008). Therefore, CSP integration could have a greater impact with these plants by offsetting more crude oil, crude oil that could exported. Electricity dispatchability is still a challenge with CSP plants, but dispatching stored water is not. Therefore, using CSP to desalinate water and store the water can be another potential study. Therefore CSP dispatchability increases via the dispatchability of clean water that was desalinated by energy provided from CSP. Integrated solar combined cycle plants are also another potential research topic that could prove beneficial to CSP integration in Saudi Arabia[1].

Many of power plants in Saudi Arabia are combined cycle natural gas power plants. Since power generation from CSP is similar to conventional power plant generation, hybridizing CSP with a combined cycle may be a good solution, especially since Saudi Arabia uses natural gas to power half of the electricity generation. With the integration

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[1] In a recent news story, Saudi Arabia recently has plans to construct the world's largest concentrated solar thermal water desalinization plant which is expected to produce 30,000 cubic meters of clean water per day by 2012. This only the first of three phases in the project. The second phase will be the construction of a 300,000 cubic meter facility. The third phase will be a more solar-power desalinization plants at multiple locations (Rao, 2010).

of CSP into a power plant, balancing the transmission load will be less of a concern. The solar aspect of the integrated solar combined cycle plants will decrease the natural gas consumption of the plant. There is also the potential to anticipate drops in electricity generation from a CSP plant and offsetting that with generation from the local combined cycle plant.

Appendix

List of solar energy projects conducted by the ERI, KACST

Projects	Location	Duration	Applications
350 kW PV system (2155 MWh)	Solar Village	1981–87	AC/DC electricity for remote areas
350 kW PV hydrogen production plant (1.6 MWh)	Solar Village	1987–93	Demonstration plant for solar hydrogen production
Solar cooling	Saudi universities	1981–87	Developing of solar cooling laboratory
1 kW solar hydrogen generator (20–30 kWh)	Solar Village	1989–93	Hydrogen production, testing and measurement (laboratory scale)
2 kW solar hydrogen (50 kWh)	KAU, Jeddah	1986–91	Testing of different electrode materials for solar hydrogen plant
3 kW PV test system	Solar Village	1987–90	Demonstration of climatic effects
4 kW PV system	Southern regions of Saudi Arabia	1996	AC/DC electricity for remote areas
6 kW PV system	Solar Village	1996–98	PV grid connection
Solar seawater desalination			
PV water desalination (0.6 m^3 per hour)	Sadous Village	1994–99	PV/RO interface
Solar-thermal desalination	Solar Village	1996-97	Solar distillation of brackish water
PV in agriculture (4 kWp)	Muzahmia	1996	AC/DC grid connected
Long-term performance of PV (3 kW)	Solar Village	Since 1990	Performance evaluation
Fuel cell development (100–1000 W)	Solar Village	1993-2000	Hydrogen utilization
Internal combustion engine (ICE)	Solar Village	1993–95	Hydrogen utilization
Solar radiation measurement	12 stations	1994–2000	Saudi solar atlas
Wind energy measurement	5 stations	1994–2000	Saudi solar atlas
Solar dryers	Al-Hassa, Qatif	1988–93	Food dryers (dates, vegetables, etc.)
Two solar-thermal dishes (50 kW)	Solar Village	1986–94	Advanced solar stirling engine
Energy management in buildings	Dammam	1988–93	Energy conservation
Solar colletors development	Solar Village	1993–97	Domestic, industrial, agricultural
Solar refrigeration	Solar Village	1999–2000	Desert application

(Alawaji, 2001)

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Vita

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